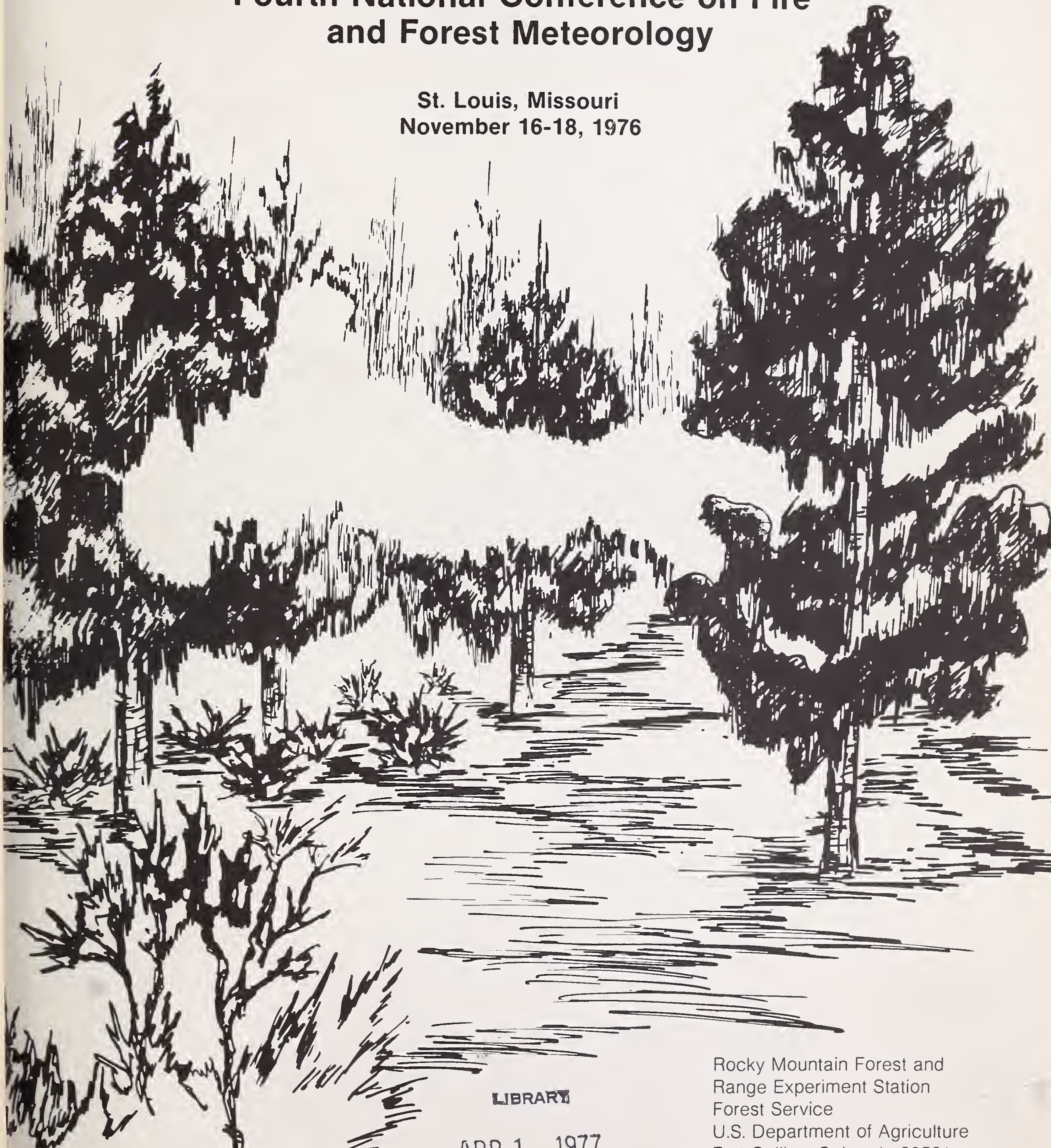
USDA Forest Service
General Technical Report RM-32

Proceedings of the

Fourth National Conference on Fire and Forest Meteorology

St. Louis, Missouri
November 16-18, 1976



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Research papers contained in this volume are based on presentations at the Fourth National Conference on Fire and Forest Meteorology held in St. Louis, Missouri, Nov. 16-18, 1976. Each session contains a number of invited papers surveying the session topic, as well as contributed papers. Sessions were held on: land managers' needs for weather service and advice; current weather forecasting capabilities; fire danger and weather; atmospheric aspects of forest insect and disease control; meteorology and land use; and influence of atmospheric pollutants on biological systems.

Keywords: Forest meteorology, fire danger, fire weather, atmospheric pollutants.

About the cover:

Artist's interpretation of smoke drift through a forest clearing.

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Cosponsored by: Society of American Foresters; American Meteorological Society; and Rocky Mountain Forest and Range Experiment Station, central headquarters maintained at Fort Collins in cooperation with Colorado State University.

Preface

The Society of American Foresters and the American Meteorology Society are service-oriented professional organizations. Each is dedicated toward advancing the capabilities of its membership in their respective fields. This conference, the fourth of its kind, is designed to provide a common meeting ground for the two relatively disparate disciplines.

Its purpose is to explore the special weather forecast needs of forest and grassland managers, the extent to which the needs are being met, and to investigate possible directions of change. The participants, speakers and listeners alike, will determine the effectiveness of the conference, more by their subsequent actions than by those displayed during the meeting.

On behalf of the host, the Society of American Foresters, sincere thanks are extended to the members of the Missouri Chapter of the Society of American Foresters for their excellent effort in providing the facilities and local arrangements for the Conference.

Quick publication of these proceedings depended on the cooperation of the authors in preparing their papers in final form, ready for photo-offset reproduction.

Foreword

The fourth of a series of conferences jointly sponsored by the Society of American Foresters (SAF) and the American Meteorological Society (AMS) was held at St. Louis, Missouri, November 16, 17, and 18, 1976. The conferences have been generated by the Fire working group of the SAF and the Fire Weather meteorologists in the AMS, and have, in the past, been directed primarily at fire-weather forecasting.

The 1976 program was developed in recognition of the expanding needs of Land Resource Managers for meteorological services. These needs include fire-weather forecasting, in addition to specialized services for pest management, recreation, forest operations such as harvesting, site preparation and reforestation, and range management.

During this conference, Federal, State, university, and private participants defined their varied weater-related concerns. The meteorologists, Federal, State, and private, provided some insights into the abilities, limitations, and problems which are a part of developing service policies.

Some examples of statements developed in the conference are:

- Resource managers expressed a need for well-equipped weather stations, operated year round by the land management agencies, to provide weather data not currently available to meteorologists.

- The National Weather Service stated a policy of providing special emphasis on forestry meteorology, including fire-weather forecasting.

- Land managers defined an urgent need for land management agencies to develop meteorological interpretive capabilities within their organizations.

- University spokesmen expressed the need for the inclusion of meteorology in forestry curricula and for career opportunities for university-trained meteorologists in land management agencies.

These are not unusual statements of policy and need. Placed in the context of this conference, however, with speaker presentations and discussions providing emphasis and reinforcement, the tone of the conference implied increasing attention toward the use of meteorology in land resource management.

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Keynote Address

Rexford A. Resler[1/]

Today we are living in what has been appropriately described as the age of the environment. As meteorologists, foresters and forest-meteorologists, we have a vital responsibility in this new age. Much of the task of balancing very real resource needs with environmental constraints will fall to us.

There was a time not too long ago when many thought of the environment as essentially fixed and unchanging. Today, we know that this is not the case. Our knowledge of the environment, and of the natural resources, has multiplied many times over. Now, we have to seek the information, knowledge and skills required to harmonize human needs for resource use with environmental safeguards. And, as the old song goes, "you can't have one without the other," although there are those who would advocate all-out resource use without environmental safeguards or, at the other extreme, environmental protection achieved at the cost of very limited resource use. We can not side-step the issue. The problems of environmental management must be attacked head-on, and I believe our profession must play a key role in finding realistic, workable solutions.

Forestry and the atmospheric sciences may well provide some of the most fundamental contributions toward shaping our future environmental programs. Let's examine some areas where we are already working together, and others where we should be working together.

Perhaps no other issue today commands more attention, from both government leaders and the man-on-the-street, than the problem of energy. The gloomy statistics on world fuel reserves are only one facet of an immensely complicated issue. We are now becoming aware of the great impact which accelerating use of fossil fuels may have on our atmosphere--and, in turn, on the total climate of the earth. I don't need to tell you that combustion of fossil fuels produces significant amounts of carbon dioxide that is injected into the atmosphere, where it enters the carbon cycle. If the rate of production exceeds what can be used by the forests and oceans, the excess becomes a permanent constituent of the atmosphere, where it greatly enhances the "greenhouse effect". I am told that theoreticians have projected a rapid warming in the earth's atmosphere after about the year 2000--resulting from the excess carbon dioxide released by burning these fuels.

This problem has a forestry component. The absence of sound land and forest management in some parts of the world is contributing significantly to the CO_2 problem. The great tropical forests represent one of the principal reservoirs for storing excess carbon. If they are harvested too quickly, without proper management, as seems to be the case in some areas, we will soon begin to increase the carbon dioxide pollution.

The handwriting is on the wall, and although the interpretation of its message may vary somewhat, the conclusion seems inescapable: unless we develop and practice management techniques to restore the great forests of the world while finding suitable substitutes for fossil fuels, we may face grave climatic difficulties in a few decades.

While I am on the subject of climatic change let me just mention another opportunity for meteorologists and foresters to work together. I don't think I need to offer data to convince you that forests, to a certain extent, make their own climate and strongly influence the climate of surrounding areas. Some scientists have hypothesized that the advance of the world's deserts has resulted from inadequate management of the forests and rangelands that formerly occupied these sites. I don't know the current state of such theories, but I do know that Forest Service studies very clearly show a strong relationship between forest vegetation systems and the atmospheric environment.

One of the most pressing problems involves the effects of pollution on the trees themselves. Air pollution has caused loss of vigor and severe mortality in ponderosa pine stands in southern California and in other conifers and hardwoods in the East. Coupled with the increasing acidity of the precipitation, particularly in the northeastern United States,

1/ Associate Chief, USDA Forest Service, Washington, D.C.

these matters must command the immediate concern of our professions if we are to maintain the vegetative systems necessary for a quality environment.

The issues which I have discussed so far are fundamental and universal in scope. Now I'd like to turn to some of the day-to-day management options which will also require the talents of both foresters and meteorologists. Cooperation in forest protection comes to mind first. There is a long history of close collaboration between foresters and meteorologists in fire control. As you probably know, the Forest Service view concerning the role of fire in the forest is changing--from one of fire control to the broader concept of fire management. Fire management involves both use of fire and protection from fire, recognizing that fire of itself is neither good nor bad, except as its effects promote or hamper the management objectives for the land.

A moment's reflection will tell you that this view of fire requires a far more intense and sophisticated use of weather information than was needed in the past. Take, for example, those approved fire plans that authorized exceptions to the "10 a.m. policy." The need for accurate weather data, reliable predictions and their proper application to fire behavior projections are far greater than under the more traditional policy. As a matter of fact, it is not an overstatement to say that the success of this new fire management program will depend almost totally on the quality of the meteorological support which it receives.

While we know a great deal now about how meteorology and forestry should be joined in fire management, we do not have the same level of knowledge for our insect and disease control programs. It is obvious that weather conditions play a decisive role in the outbreak and spread of insects and disease. But we have no means of systematically incorporating these effects into our control strategies or into the day-to-day decisionmaking. I am very pleased to see that this conference has set aside an entire session for the discussion of this problem.

As land managers we are also faced with a major task in land management planning, which requires help from our meteorologist colleagues. The Clean Air Act and the subsequent implementing regulations require that each State classify its land into three categories, ranging from areas in which any degradation of air quality would be prohibited, to areas which would tolerate pollution levels up to the national or local standards. The last Congress considered, but did not pass, legislation which would have placed areas such as National Parks and classified wilderness in class 1, thus prohibiting any degradation of air quality. Since air pollution can travel long distances from the sources, non-degradation air quality standards could have a profound effect on land use decisions and benefits. There's little doubt that similar legislation will again be introduced in Congress.

Meteorologists will have to help land use planners find the answers to a number of questions. For instance, how large must buffer zones around class 1 areas be in order to provide sufficient dilution to meet the required air quality standards? What constraints will these buffer zones place on forest and range practices and use of our renewable resources? And what are the cost implications? Who is going to pay for them?

In another area of current concern I should mention the Resources Planning Act, calling for a continuing assessment of all the multiple resources of the Nation's forests and rangelands. This requirement is creating a kind of revolution in Forest Service procedures--a welcome revolution, I might add. To project information properly, we must make extensive use of models for forest productivity of timber, water, wildlife, and even the social values and markets for recreation. In many areas the data requirements for these models demand meteorological and climatological information. Water and air quality are closely related to each other and form one of the resources to be assessed.

We live in a time of great challenge. One challenge is to accommodate the rapidly expanding volume of human needs for goods and services. Another challenge is to safeguard the delicate balances that make this planet Earth the only habitable place in the solar system and, so far as we know today, even in the entire universe. Forestry and meteorology promise us a perfect combination for meeting such challenges created in this age of the environment. I urge you to unite your efforts in this endeavor.

Session I

Land Managers' Needs for Weather Service and Advice

Chairman: Sam Cobb

State Forester

Pennsylvania Bureau of Forestry

Needs of State Forest Organizations[1]

J. E. Schroeder[2]

Land managers today are concerned with needs generated by an expanding population which exerts ever-increasing political social and economic pressures on an ever-diminishing wildland base. Our position as land managers and meteorologists needs to be one of constantly evaluating our changing needs and working together to develop the best system we can which will meet these needs.

INTRODUCTION

When I was invited to present the Needs of the State Forest Agencies for Land Management Weather Service and Advice, I recalled a similar assignment in Boise, back in 1971. I believe Bill Sullivan, who has a part in our second session here today, chaired that panel. However, the topic then was about fire weather needs. Today's concerns relate to the needs for weather service in the total land management program. Today we have broad based land managers concerned with an expanding population which exerts ever-increasing political, social, and economic pressures on a constantly diminishing wildland base. Environmentalism and concern for land use have become a way of life. Land managers and meteorologists have their work cut out for them to meet and hopefully stay ahead of the needs generated by these pressures.

CURRENT SITUATION

I'd like to begin by talking a little on the situation currently facing the various state agencies, the needs for weather services, and the use the states are making of services now available.

In the five years since I last discussed with you the fire management needs in the United States, the situation has not changed very much. Each year we are still averaging more than 100,000 wildland fires which consume over 1 1/2 million acres. To meet this fire load, along with other land management needs, the states employ the use of weather services according to the need. Service needs may vary according to acreage protected, number of fires, fire severity, hazard and risk. Other factors which affect service type and use are organizational peculiarities, variations in legal responsibilities, land use patterns, ownership, and degree of environmental sensitivity.

The use of weather service by the states has not changed much either -- primarily because the service offered is basically the same that has been provided for many years. Service ranges from using whatever public forecast is available, to special service forecasts, to the level of service Oregon has used for some time. In Oregon, the forecaster is fully integrated into the agency operations and his talents are used fully. Analysis, field service, system development and other user needs become an important part of the weather service pattern. This is the level of service that the states need if they are to meet the challenges of the environmental age in which we now live.

USER-PRODUCER RELATIONSHIPS

Now let's examine the relationship between the weather service and the state land and fire management agencies. First we need to state the objective of the weather service in general and the fire weather forecaster in particular. Thinking of the forecaster as a producer, the objective of the producer is to meet the weather

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1/Paper presented at Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.
2/State Forester of Oregon, 2600 State Street, Salem, Oregon 97310

needs of the user.

In order for the producer to best meet these needs, he first has to develop a good working relationship with the user. The best way to accomplish this is to integrate the producer right into the user's organization. This can be accomplished in two ways. Wherever possible, the producer should be located at a headquarters of the user, with the headquarters selection to be based on individual user needs. If this is not possible or desirable because of geography, number and variety of users or other reasons, the producer should be located as close as possible to the user. With this inter-agency integration the forest manager-meteorologist team is better able to address the variety of problems and needs. The system produces improved mutual understanding, communication and training opportunities for the forest manager and the meteorologist alike.

FIRE WEATHER SERVICE ORGANIZATIONAL DEVELOPMENTS

Turning our attention to some of the things that have happened in the weather service organization during the past several years, back in 1971, I reported on two trends which I felt weakened these strong user-producer ties which are so greatly needed if we are to reach our mutual objective. One was integration of fire weather meteorologists and other specialists into the general forecasting system and the other was centralization. We were particularly concerned about the integration of specialists because it undermined the weather service objective. We opposed it then and we still oppose this type of organizational integration. Meteorological service to our land managers has continued to decline in the face of increased and broader needs. Our concern about this problem is greater than ever.

CURRENT NEEDS

Now, let's talk about some of the other key needs in the present weather service:

(1) Communications. As mentioned earlier, the need for weather service is no longer confined to just fire related activities -- it is needed to respond to such activities as scheduling reforestation, smoke management, forest aviation, spraying, seeding, fertilization, nursery activities, surface transportation, photography, and freeze, wind and water warnings. A complete user-producer teletype intertie is needed if we are to adequately serve these new and expanding fields of forest weather.

(2) Additional Weather Data: Another current need is for additional weather data. It seems that this goes hand-in-hand with the ever-increasing complexity of use and need facing the forest manager and the meteorologist. Two things that come immediately to mind are the need for additional upper air data and standardized and upgraded weather observation stations, including automatic data collection.

(3) Forecasting. Then, of course, there is the usual laundry list of needs in the area of forecasting. Some of these are tailoring forecasts to areas of homogeneous climatology, improving accuracy, providing seven-day-a-week service, and detailing of long-range forecasts. Most important, the National Fire Danger Rating System is reaching the final development stage. John Deeming will give us the latest developments tomorrow. At any rate, it looks good. We should look forward to full adoption by all agencies and tailoring our forecasts to this system.

FUTURE NEEDS

Now I would like to discuss our future needs and to do this I am going to confine my remarks to the four subjects of (1) environment, (2) research and development, (3) planning and projection, and (4) budgeting.

(1) As I stated at the outset, land management agencies are rapidly becoming transformed into environmental agencies concerned with a variety of land uses. As this transformation takes place, there also needs to be a transformation in weather service. I don't think this point can be emphasized enough. Not only is the weather scope being broadened to new fire and land management related fields, but the period of forecasting need is also being extended. As an example, smoke management requires more detailed service on a year-round basis. We need to be taking a real good look at all these new areas which keep springing up and try to develop an environmental approach so that we can meet the challenges as they arise.

Just to illustrate the changing pattern in forecasting needs, in 1975 the Salem, Oregon, Fire Weather Office issued 513 smoke management advisories, 346 fire weather forecasts, 120 spraying advisories, 9 nursery advisories and 9 burning advisories. Smoke management advisories are becoming far more detailed. For example, smoke management forecasts routinely forecast timing and velocity of sea breezes through coast range passes in western Oregon. Spraying forecasts are ever-increasing primarily to meet the needs of herbicide applications in

reforestation and the challenges of large scale insect control projects, such as the Tussock moth infestation which plagued the northwest states during the past few years. In many instances continuous field forecasting is required in order to get these jobs done. Nursery forecasting has also been on the increase. Nursery managers are concerned with minimum temperatures, abnormally warm or cold periods, snow and heavy rainfall. Weather conditions are extremely important to lifting operations, tree damage and survival.

In addition to advisories and forecasts, almost daily pilot briefings are conducted for aerial photo projects, insect and disease surveys, and air transportation.

(2) Research and development are platforms of progress in weather service just as they are platforms in other fields. Looking ahead on the program, I note that you will be hearing about some specifics in research, especially on Wednesday and Thursday. I only want to emphasize the need to continue and to push forward in this direction. But before I leave this subject, I would like to pass on some of the highlights of a meeting held last May in Portland, Oregon, where 35 top managers, meteorologists, teachers and researchers gathered to address the topic "Meteorological Needs in the Pacific Northwest". Although these highlights expressed here are regional in nature, I am sure they have meaning to all of us. First, the group expressed a need for greater application of climatic data to land use management. Examples cited were frequency and severity of drought, effect of precipitation on roads and soils, the development of resource cost to loss ratios based upon weather occurrence and the selection of recreation sites.

Second, the group endorsed NOWCAST -- a pilot program proposed in Oregon utilizing a television network for a continuous dissemination of weather information. We see great possibilities for this program, particularly in the areas of fire prevention, regulated use of wildlands and smoke management.

Third, this group also emphasized a theme I have already mentioned several times in my remarks here today. That is the increased need for expanded weather service for such land management activities as reforestation, spraying, aerial surveys and general air operations and road construction and oiling.

(3) Planning and projection are closely aligned with research and development. What we need to accomplish here is to project the entire future land management system. Then we need to project the weather service that will be needed to serve this system. The last projection for fire weather system needs was incorporated in the "Federal Plan for a National Fire Weather Service" which outlined a nine-phase improvement plan to be achieved during the 1968-1972 time period. Currently, about four and one-half phases -- or about half the plan -- have been completed; right where we were five years ago. We are still behind schedule on this improvement plan and we need to catch up.

(4) This brings me to the last of the four subject areas I outlined in beginning the discussion on future needs. This is one dear to all our hearts -- money. There seems to be a perennial problem with budget deficiencies in the weather service, just as we have everywhere else. The state agencies are concerned about this problem and stand ready to assist in any way they can. One possible way to assist would be to follow the procedure used in obtaining a restoration of Clarke-McNary allotment funds. In this effort the state foresters pursued a unified and vigorous approach through their respective delegations in Congress to achieve the goal of increased funding for this vital program.

CONCLUSION

I have attempted in this presentation today to discuss the present services and future weather needs without reservation. In conclusion I would like to add that our position as meteorologists and forest managers needs to be one of constantly evaluating our changing needs and working together to develop the best user-producer system we can which will meet these needs.

I greatly appreciate the opportunity to appear here today. If the program is any indicator, this should be the best meeting we have ever had.

Thank you.

Land Managers' Needs for Weather Service and Advice[1]

Jack F. Wilson[2]

Abstract. Fire weather needs in the U.S. Department of the Interior are highly variable both as to the missions and philosophies of the eight agencies involved. Weather requirements of USDI agencies range from short range meso scale data required by fire line personnel through the full range of weather services to the long range outlooks needed for seasonal planning purposes.

INTRODUCTION

Land management need for weather service and advice within the Department of the Interior is far too broad a topic for discussion at this session. The geographic range and the program complexities embraced by the USDI would require the consideration of all facets of weather services and would encompass such an extensive area of discussion as to be unmanageable. So, with your permission, I'll narrow this topic down to fire management needs within the USDI, recognizing that this topic also is broad.

While it might be somewhat elementary to many of you, the USDI supports fire missions in eight of its agencies, and vastly differing weather needs exist for each agency. Let me cite examples of these missions and philosophies.

AGENCY MISSIONS AND PHILOSOPHIES

Bureau of Land Management

In BLM, my own agency, the overall mission is briefly defined as "to manage all the resources for which it is responsible to provide maximum public benefit both currently and in the future, and with full consideration for good conservation practices and for protection and enhancement of the environment. (USDI Manual 135.1.2)"

Its fire philosophy briefly states, "take aggressive action on all new fires with sufficient force to contain the fire in the first burning period." If it escapes, the policy is to back off and assess resource values, costs, rehabilitation possibilities and environmental damage, and man or not man accordingly. (BLM Manual 9210.06C)

National Park Service

The mission of the NPS "is that portion of the public lands /are/ reserved from settlement, occupancy, or sale and set apart as public parks or pleasuring grounds for all people. (USDI Manual 145.2) Their fire philosophy is best enumerated in Staff Memo 72-12." While some natural areas with a history of naturally ignited fires, or historic areas with a fire subclimax setting, may need to significantly change their plans and programs, other areas will continue full fire "control."

Bureau of Indian Affairs

BIA has the mission to encourage and train Indian and Alaska Native people to manage their own affairs under the trust relationship with the Federal Government; to facilitate full development of their human and natural resource potentials; and . . . to utilize their skill and capabilities in the direction and management of programs for their benefit. (USDI Manual 130.1.2)

Insofar as their fire policy is concerned, the best philosophy can be gleaned through reading 53 IAM 12.4. In essence, it is a control philosophy and is as one would expect in view of the trust nature of BIA's responsibilities. BIA has, however, been in the lead in the use of fire in forest management,

1/Paper presented at Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.

2/BLM Director, Boise Interagency Fire Center, Boise, Idaho.

particularly in the southwestern United States.

Fish and Wildlife Service

The F&WS mission is to (1) assist in the development and application of an environmental stewardship ethic for society based on ecological principles, scientific knowledge of fish and wildlife, and a sense of moral responsibilities, (2) guide the conservation, development, and management of the nation's fish and wildlife resources, and (3) provide the American public with opportunities to appreciate, understand and use wildlife resources. (USDI Manual 142.1.1B)

Their fire philosophy is not set forth in any guidelines that I can find, but a general ethic exists within F&WS that better grass and wildlife forage will replace existing vegetation if fires in brush and grassland are set, or allowed to burn. Fire suppression on wildlife refuges are usually contracted to other protection agencies.

In addition within the Department, several other agencies have minor fire activities. These agencies include the U.S. Bureau of Reclamation, the Bureau of Mines, the Bonneville Power Administration, and the Office of Territories.

NECESSARY FIRE WEATHER FORECAST AND SERVICES

From all the foregoing, you would expect the needs for fire weather services to be varied. The need for weather service of a BIA worker to burn logging slash on the White River Agency in Arizona is far different from that of a Park Ranger in Sequoia National Park who must determine whether or not to take action on a fire.

So also are the needs for weather services different for succeedingly higher echelons in the administrative chain. A very specific site requirement exists for a Fire Boss who needs to know what winds to expect in Whiskey Creek at 3 p.m. because winds are critical to him for control purposes. His boss, a District Fire Control Officer, may be more interested in a broader forecast for tomorrow for his district. His counterpart at the State level needs the same kind of information, but on a much wider geographic base. A major coordination center, such as Boise Interagency Fire Center, needs longer range, broader geographic data, and can utilize less precise or verifiable data. These data include continuous monitoring of antecedent moisture and fuels growth conditions, as an example the Palmer Drought Index, moisture indices, seasonal accumulated stream flow, soil moisture information, etc. Beyond that, there is a need for data systems to massage the extensive climatological data into fire planning systems. For example, in 1965 fire danger ratings were among the highest recorded, yet there were few large fires in 1965. Why? The answer was found in the painstaking analysis of relative humidities for that year. While they were only 2 percent to 3 percent higher than usual, that was enough to keep large fire incidence low.[3/]

Forecast/outlook information often strongly influences higher level decision-makers regarding major mobilization, prepositioning, or demobilization decisions. We recognize the scientific and perhaps legalistic constraints with which the National Weather Service must contend, and many other factors are also considered, but we need the best advice on pending weather events that we can get. Frequently, we get a lot of benefit from such questions as: Will the lightning storm be wet or dry? When will the front hit Kimama? And so on. We know these are judgment factors and are often the fruits of years of experience, and we'll continue to ask these questions--recognizing full well the limitations that are built in.

Another emerging area that needs climatological analysis and fire weather counsel is in fire management area planning. The NWS has not been involved very much here. What weather parameters should be built into management prescriptions? An example of what can happen without this sort of input occurred in Michigan in late August on the Seney Wildlife Refuge. A fire that under normal weather conditions for that area would not have become a problem, became a costly suppression problem under the severe drought conditions that exist this year. If the parameters are properly identified, then the assessment and monitoring systems become important and need Weather Service guidance.

And finally, a very important aspect is to recognize the need and to acknowledge the excellent service that Fire Weather Forecasters are providing to the fire training programs. The course development, tasking, and curriculum content, as well as the instruction itself, are vital to training fire personnel. As fire management becomes much more costly and sophisticated, the need for quality weather inputs will increase at all management levels. I would hope and anticipate the National Weather Service will make increased resources available to help fire control agencies continue to meet their changing needs.

3/ Personal efforts supported by Charles Seaverson, NWS 1965/66.

Department of Agriculture Needs for Specialized Weather Forecasting[1]

W. R. Tikkala 2/

The historic need for special weather forecasting has been identified with fire protection. Supplemental weather stations have been installed and operated for this purpose. The need for specialized weather service in other forest management operations should be recognized and appropriate measures should be taken to provide the basic weather information to the forecasters. The procedures for inclusion of weather judgements in resource management should be developed. Special forecast services provided by NWS should be strengthened and expanded.

This conference is an extremely interesting one. The first three joint meetings were dedicated mostly to the scientific aspects of fire weather. The managerial and policy making portions of the meteorology--forestry mix have not been a subject for discussion in these meetings. In this respect we have probably been guilty of the "talking to ourselves" syndrome. This conference will not only give us a chance to examine the full scope of forestry needs in the special forecasting area of the meteorological services, but will also permit some examination of the various approaches to meet these needs.

For many years foresters and meteorologists have enjoyed a close working relationship, especially in responding to emergencies. Most of the emergencies have been fire related, although occasionally hurricanes and floods have been involved. The increasing needs and demands for forest resources have created an expanded set of more specific requirements for meteorological information to support planning and decision making by forest managers.

We might begin by examining some of the general characteristics of the meteorological information required by management. First of all, the information must be timely in that it must relate directly to those time periods over which the decision will be applicable. It must be site specific; that is, the information must be applicable to those locations on which management decisions will focus. Finally, it must have proper form and quality for direct use in decision making.

To see the evolution of these needs, we might explore some of the historic approaches to the use of meteorological information, as practiced by foresters in the Department of Agriculture. These uses were identified early in the management planning of the U. S. Forest Service, the primary forest management agency in the Department. There was quick recognition of the importance of predicting weather in the fire protection segment of resource planning. Supplemental weather stations were developed at district headquarters, and firemen became adept at relating temperature, wind, and humidity to the incidence and growth of fires. Fire Weather forecasters were assigned by the National Weather Service to provide close scrutiny to the weather elements that affect fires. Weather stations became known as fire danger stations, and were manned, financed, and supervised by fire control personnel.

However, the management of forests and grassland has expanded beyond the fire protection status which spawned the fire danger station. Some of the areas where meteorology should be of concern to foresters are:

- Reforestation of lands which have been deforested through one means or another, is an extremely critical undertaking. Precise

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1/ Paper presented at the Fourth Conference on Fire and Forest Meteorology, St. Louis, Missouri - November 16-18, 1976.

2/ W. R. Tikkala, Director, Cooperative Fire Protection, U. S. Forest Service, Washington, D. C. 20250.

knowledge of amounts, kinds, duration, and timing (seasonal) of precipitation in an area to be reforested is essential. Depth of snow cover, moisture content of the soil, probability of frost, and selection of the proper tree species all have a bearing on when and how to reforest.

- Logging should be planned around soil moisture, snow depth, periods of heavy rain, and periods of low humidity. Such planning during sale preparation can have a tremendous beneficial effect on sale layout, landings, equipment requirements, debris utilization, and reforestation. A sale designed for helicopter operation could be considerably more attractive if the prospectus listed the average number of hours per day and days per month a helicopter could operate.

- Engineering--the design of roads, culverts, bridges, administrative sites all require precise knowledge of kinds and amounts of precipitation, wind direction and probable velocity, and other related weather information.

- Recreation--both winter and summer recreation planning involves the impact of weather on humans. Snow, ice, winds, and avalanches have a marked effect on the recreationist, as do high summer temperatures, lightning, storms, possible wildfires and drought. Planning recreation facilities suggest a need for close liaison with meteorologists.

- Insect and disease management in the forest environment is dependent on accurate meteorological information. Forest pest population fluctuations are controlled principally by food and weather. Our ability to anticipate pest population eruptions rests directly on our knowledge of host susceptibility to attack and understanding of weather patterns which are favorable to the pest. The successful execution of aerial suppression operations to control forest pest outbreaks is also influenced by meteorological factors. The ability to accurately predict pest development rates and meteorological episodes potentially detrimental to treatment effectiveness is extremely important in timing aerial suppression projects.

I mentioned earlier the close operational ties between fire protection and the forest network of weather stations. There are about 1800 of these stations nationwide, operated by State and Federal agencies. Their use is almost exclusively keyed to fire danger. These stations supplement National Weather Service facilities, and serve to fill gaps in the data collection process. Perhaps one of the keys to expanding cooperation with meteorologists in forestry related weather operations is the use of these weather stations. We should consider year round operations, multiple purpose locations, and broad scale analysis of data.

Forecast centers, as envisioned by the NWS will provide computerized predictions of weather, on a large scale, based on the best predictive skills available in the programming and interpretation of weather inputs. On this scale, a reasonable product should be the best mass-use, general purpose forecast.

The person who is planning to put a large crew into action setting fire in 40 ton per acre slash cannot rely on mass-use, general purpose forecasts. He is playing with fire, in the true sense of the term, when he commits himself to such an action without the most precise weather information available. For this reason, specialized, localized, unique forecasting services are required. They are not required however in every month of the year in most locations.

The analysis of fire weather patterns, high snowfall areas and other weather elements which influence the expenditure of large amounts of money in recreation, reforestation, and engineering is also necessary. Whether this is done by the NWS, by contracting forecasters or by agency personnel will depend largely on availability of manpower and cost/benefit considerations. Logically, the NWS would appear to be the best source of this service. These are specialized services, and decisions need to be made on the extent of specialization which is justifiable.

At any rate, the meteorologists and the foresters are the building blocks to expand consciousness in applying meteorology to resource management. I suggest that the needs of the Department of Agriculture in forestry are broad-much broader than current operations would indicate. I also suggest that an expansion of the special forecast services offered by the NWS is necessary, and that forest managers and meteorologists both have a responsibility to expand these horizons.

Session II
Current Weather Forecasting Capabilities

Chairman: Jack S. Barrows, Professor

Department of Forest and Wood Sciences

Colorado State University

Fort Collins, Colorado

Current Capabilities in Prediction at the National Weather Service's National Meteorological Center[1]

Edwin B. Fawcett[2]

Abstract.--The state-of-the-art in numerical weather prediction at the National Meteorological Center in Washington is reviewed. In particular, the use of fine-mesh models and their application to the prediction of precipitation, temperature and wind is described. Considerable progress has been made at NMC in the use of fine-mesh models during the last 5 years. NMC is also experimenting with the use of very-fine-mesh models to improve precipitation forecasting. In spite of this progress, there are still limitations to our overall skill in forecasting. The meteorologist in the NWS still plays an important role in evaluating and improving the numerical product. Important problems remain in application of numerical techniques to the forecasting of small-scale weather phenomena, such as thunderstorms and heavy precipitation.

INTRODUCTION

Operational numerical weather prediction began in the United States in 1954 with the organization in Washington, D. C. of the Joint Numerical Weather Prediction Unit, staffed by meteorologists from the Weather Bureau, Air Force, and Navy. The first operationally useful NWP forecasts were issued in the late 1950's, soon after the organization of the Weather Bureau's National Meteorological Center. The first operational NWP forecasts issued by NMC were based on a barotropic model, which covered most of the Northern Hemisphere (Cressman 1958). In 1962, a 3-level baroclinic model (Cressman 1963) suitable for operational use had been put into operation. Since 1966, a hemispheric 6-layer baroclinic model (Shuman and Hovermale 1968), which uses the primitive (Newtonian) equations (P.E.), has been used as the NMC operational model. A regional Limited-Area Fine-Mesh (LFM) model (Howcroft 1971) was added to the inventory of NMC's operational models in September 1971. The LFM, similar in design to the P.E. model, was run to 24 hours until early 1976, when the program was expanded to run to 48 hours. The U. S. forecasting community now receives forecasts from the barotropic, hemispheric P.E. and regional LFM models twice each day, based on analyses made from 0000 and 1200 GMT observations.

This paper reviews the progress since 1955 in prognosis of synoptic-scale systems, and then discusses the application of NWP to the forecasting of specific weather parameters (e.g. temperature, precipitation, wind, etc.). The skill of some of these specific forecasts is also reviewed. Finally, results are shown from experimental precipitation forecasts with finer-mesh models, which are being developed for future use at NMC.

PROGNOSIS OF SYNOPTIC-SCALE SYSTEMS

The easiest way to begin a discussion of the current state-of-the-art in NWP is to review the progress in prognosis of the synoptic-scale systems which control the development and movement of the smaller-scale weather systems.

[1]/Paper presented at Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.

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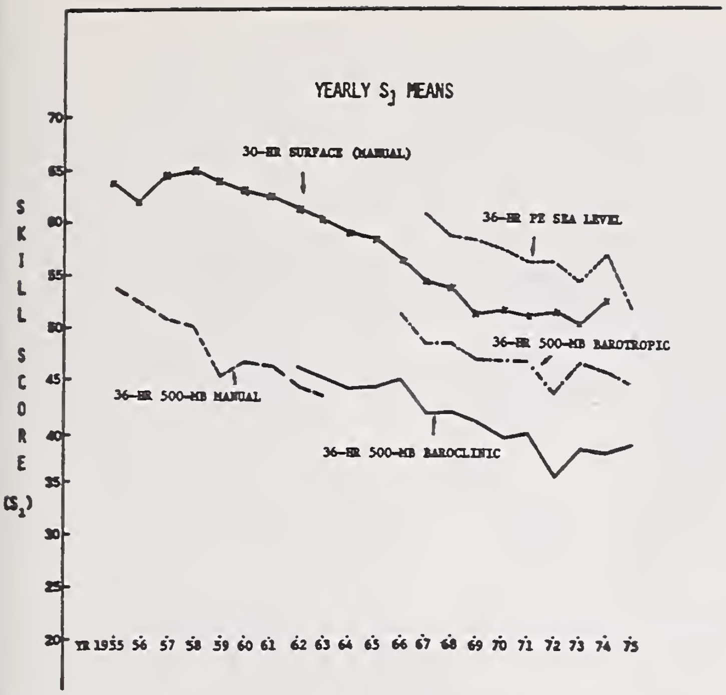


Figure 1.--Yearly mean S_1 scores for NMC's sea-level and 500-mb manual and NWP prognoses.

Figure 1 shows the skill score for twenty years of sea-level and 500-mb prognoses issued by the Weather Bureau's National Weather Analyses Center from 1955 to 1958, and by NMC since 1958. The score used is the S_1 score (Teweles and Wobus 1954) given by

$$S_1 = 100 \frac{\Sigma |e_G|}{\Sigma |G_L|}$$

where e_G = error of the forecast pressure (or height) difference, and

G_L = observed or forecast pressure (or height) difference, between grid points, whichever is largest.

The lower score is the more skillful. This score is sensitive to the distance between grid points (or stations) used in measuring the gradient errors. However, in the curves given in figure 1, consistent sets of grids have been used for verifying each prognosis, so that the improvements and differences in skill from year to year are real. Twenty years of experience with the S_1 score have shown the practical range between perfect and worthless progs to be 30 to 80 at sea-level and 20 to 70 at 500 mb.

Figure 1 illustrates the significant improvement in both sea-level and 500-mb prognoses since the introduction in 1958 of the operational 500-mb forecasts based on the barotropic model. Beginning about 1959, the skill of the manual sea-level prognoses improved, as more skillful and useful numerical prognoses became available. The improvement in the skill of manual sea-level prognoses accelerated in 1966 after the introduction of the first useful sea-level prognoses from the 6-layer P.E. model.

Manual 500-mb prognoses were discontinued in 1962 after it became apparent that they were no more skillful than the 3-layer baroclinic 500-mb prognoses then available. The improvement in the skill of the 500-mb prognoses also accelerated in 1966 after the introduction of the P.E. model. It is interesting to note the consistent improvement (6 to 8 S_1 points) of the P.E. 500-mb prognoses over the barotropic prognoses during the 10 years of comparison.

Since 1971, use of the LFM model has further improved the numerical guidance available for operational forecasting. Table 1 shows mean S_1 scores for February through May 1976. The LFM prognoses at both sea-level and 500-mb are more skillful than the corresponding large-mesh progs, except at 12 hours over the western U.S.

Table 1.--S_1 scores for large-mesh P.E. versus fine-mesh P.E. (LFM) over eastern and western U.S. (Feb. through May 1976)

		EAST OF DENVER			WEST OF DENVER		
		P.E.	LFM	P-L	P.E.	LFM	P-L
12 HR FCST	S.L.	38.2	37.9	+0.3	42.1	42.5	-0.4
	500-mb	21.5	16.3	+5.2	25.4	22.9	+2.5
24 HR FCST	S.L.	45.8	43.5	+2.3	50.0	49.5	+0.5
	500-mb	27.5	21.5	+6.0	31.9	29.5	+2.4
36 HR FCST	S.L.	54.6	50.4	+4.2	58.3	56.8	+1.5
	500-mb	34.3	28.6	+5.7	39.4	37.1	+2.3
48 HR FCST	S.L.	63.9	59.0	+4.9	63.7	61.1	+2.6
	500-mb	40.7	36.3	+4.4	44.8	43.4	+1.4

The improvement of the LFM over the P.E. increases with time at sea-level, where the use of a finer mesh improves the definition of smaller-scale systems. At 500-mb this improvement levels off and decreases after 24 hours due to the smoother less detailed 500-mb flow patterns observed and forecast. Table 1 also shows that both the large- and fine-mesh models are less skillful over the western U.S. Users of numerical guidance have noted this fact for many years. Failure to correctly model the

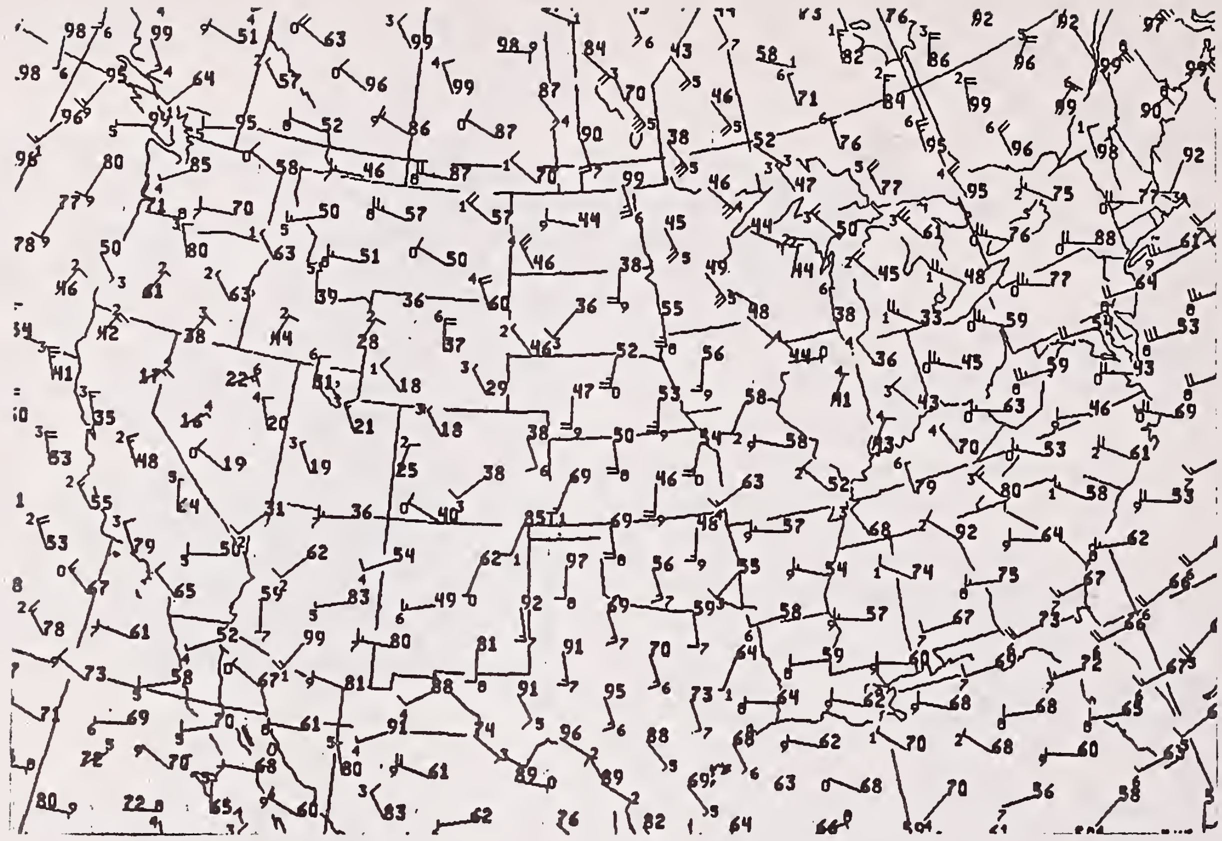


Figure 2.--Twelve-hour prognosis of boundary layer winds and mean relative humidity from NMC's regional (LFM) model, valid at 0000 GMT 13 July 1976.

details of the complicated terrain effects on the atmosphere and the absence of observations over the Pacific are suspected as causes for this difference in skill.

USE OF NWP IN FORECASTING WEATHER ELEMENTS

The increased skill which has been demonstrated in forecasting the evolution of synoptic-scale systems at sea-level and 500-mb illustrates only part of the story of progress in NWP. Use of winds and temperatures from NMC's P.E. model for flight planning has become very general among airlines and other aviation interests. Direct output of forecast parameters at U.S. cities (e.g., boundary-layer winds, layer humidities, vertical velocity and lifted index) from the LFM in bulletin form are available twice each day via request-reply from the FAA's weather switching center in Kansas City. These parameters are very useful to the forecaster in the prediction of precipitation. An example of the boundary-layer winds and humidities from the LFM as they are transmitted via facsimile, is shown in figure 2.

Another method of obtaining objective forecasts of local weather elements uses statistical methods to complement the output of numerical prediction models. This is the Model Output Statistics (MOS) technique in which local observations of weather parameters are matched with output parameters from numerical models for a period of a year or more. Forecast equations are then derived by statistical techniques which can account for biases and inaccuracies in the numerical model and for local climatology. The MOS technique has been applied to forecasts of many weather elements including temperature, precipitation, winds, clouds and thunderstorms by the National Weather Service's Technique Development Laboratory (Klein and Glahn 1974), and are now an important part of NMC's daily operational products sent via facsimile and teletype.

The state-of-the-art in numerical forecasting of rainfall occurrence and amount, thunderstorms, etc. is difficult to specify because most numerical forecasts of these weather elements have only become available in the last two or three years. However, useful forecasts of maximum and minimum temperatures at individual U. S. cities have been provided from NMC's computers for several years. Figure 3 shows a record of verification of these forecasts from 1968 through 1975. The steady increase in skill during the 8-layer period can be attributed to several factors,

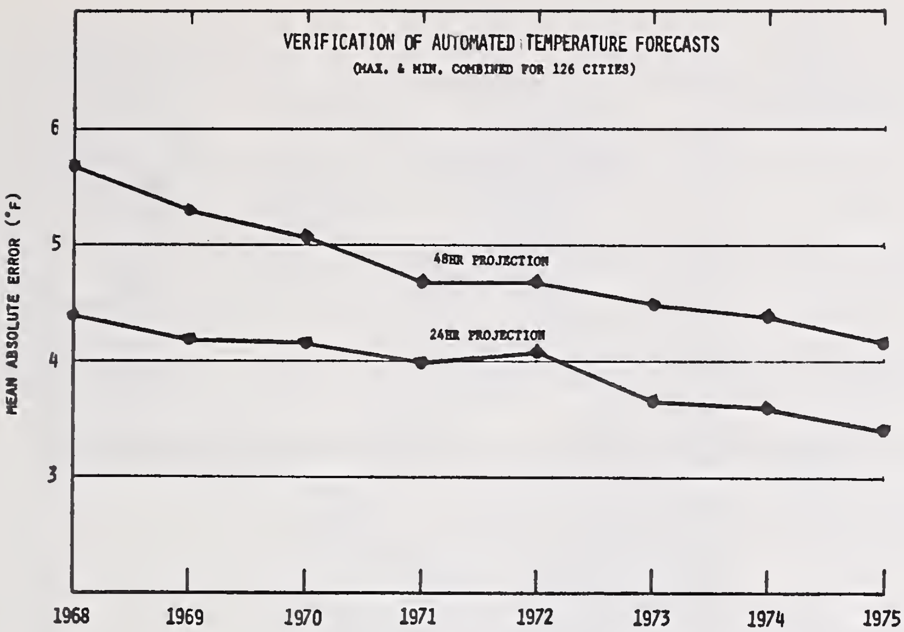
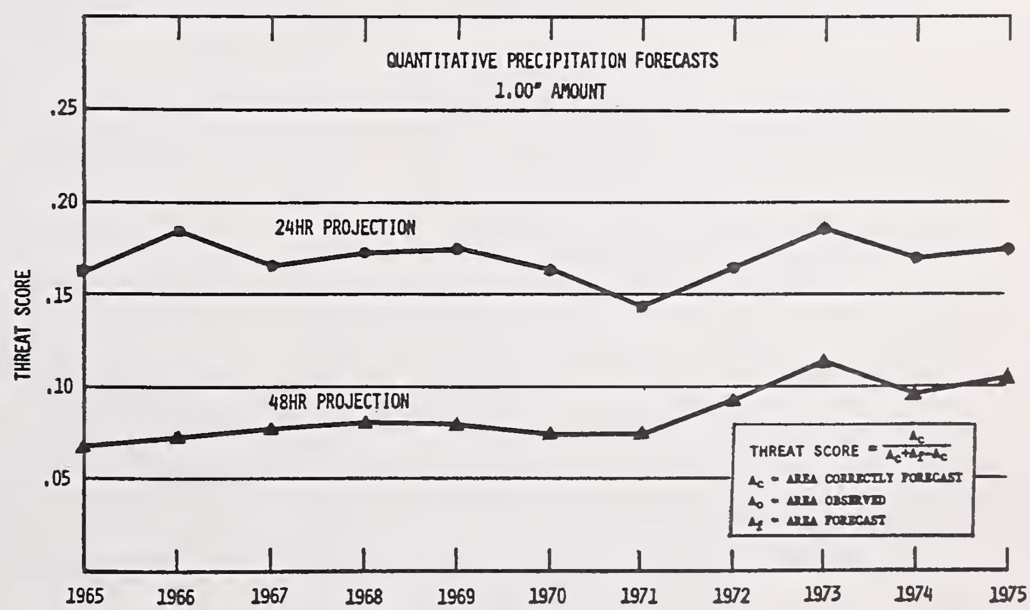


Figure 3.--Mean absolute errors of automated temperature forecasts (combined maximum and minimum) for 126 cities for the years 1968 through 1975.

such as increased skill of the P.E. model used to make the forecasts, rederivation of the equations with a larger data base, and introduction of the MOS technique in 1973.

Most weather forecasters would agree that temperature is one of the easiest weather elements to forecast. Precipitation, however, is one of the most difficult; and numerical forecasts of precipitation have been the least useful of all the output from numerical models. Weather forecasters still have to depend on personal skill and experience in interpretation of numerical guidance when making precipitation forecasts. This is particularly true for forecasts of precipitation amount. Figure 4 illustrates a ten-year record of verification at NMC in manual forecasting of areas of precipitation over the U.S. There is some evidence of slight improvement in the 48-hour projections, but this record certainly shows less increase in skill with time than the temperature verification curves or the curves for sea-level and 500-mb prognoses. If one examines the annual variation in skill of the manual QPF, the reason for the low forecast skill becomes evident. Figure 5 shows the annual variation of the maximum, minimum and mean threat scores for 24-hour forecasts of one inch or more of precipitation. Note the seasonal variation in skill. This can easily be translated into a variation of skill with the predominant scale of precipitation systems—synoptic scale in the winter to meso (or smaller) scale in the summer. Forecasters know it's harder to forecast occurrence and distribution of precipitation with thunderstorms than with winter storms.

Figure 4.--Mean annual threat scores for 24-hour projections (top curve) and 48-hour projections (bottom curve) for areas of 1" or more of precipitation during a 24-hour period; manual forecasts by NMC's QPF Branch.



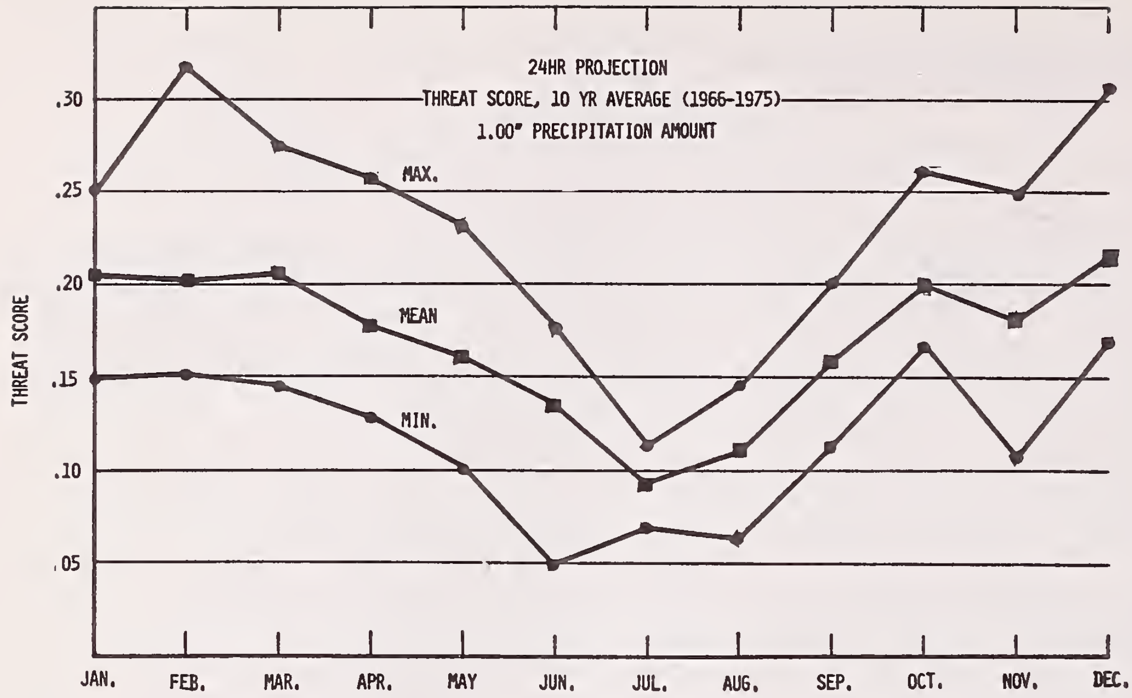


Figure 5.--Annual variation of the maximum, minimum and mean threat scores of the 24-hour projection of 1" or more of precipitation during a 24-hour period; manual forecasts by NMC's QPF Branch.

WHAT'S AHEAD IN NUMERICAL FORECASTING

One of the primary goals of NMC is improvement of operational numerical models, which hopefully will be reflected in improved forecasts to the public. Improvement of numerical precipitation forecasts is high on the list of tasks under this goal. Figure 6 summarizes the area and grid system used in some of NMC's operational and experimental models. Operational use of the LFM (regional) model on a 190 km grid has already shown improvement over the 6-layer hemispheric model on a 380 km grid.

Among experimental models now being developed at NMC, is one designed for forecasting the movement of hurricanes. The Hurricane model (Hovermale et al, 1975) normally operates on a 60 km grid and is designed to move with the storm being forecast; thus the name Movable Fine Mesh (MFM) has been applied to this model. Also, in the NMC inventory is a version of the Regional (LFM) model on a finer (95 km) grid. This is called the Very Fine Mesh (VFM) model.

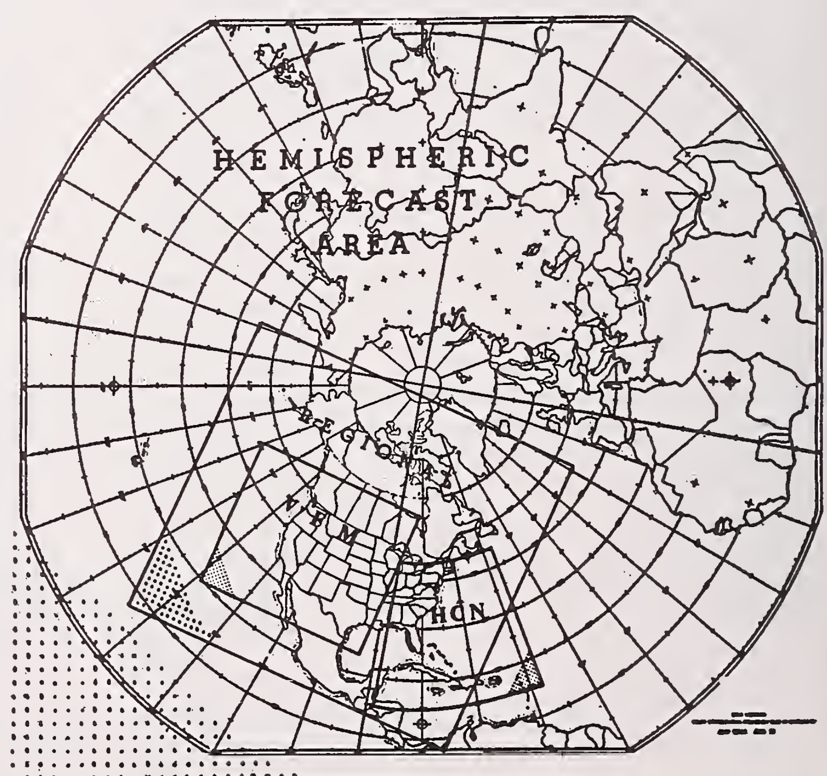


Figure 6.--Grid areas for some of NMC's operational and experimental models. The spacing of grid-points with each model is shown in the triangle in the corner of each area.

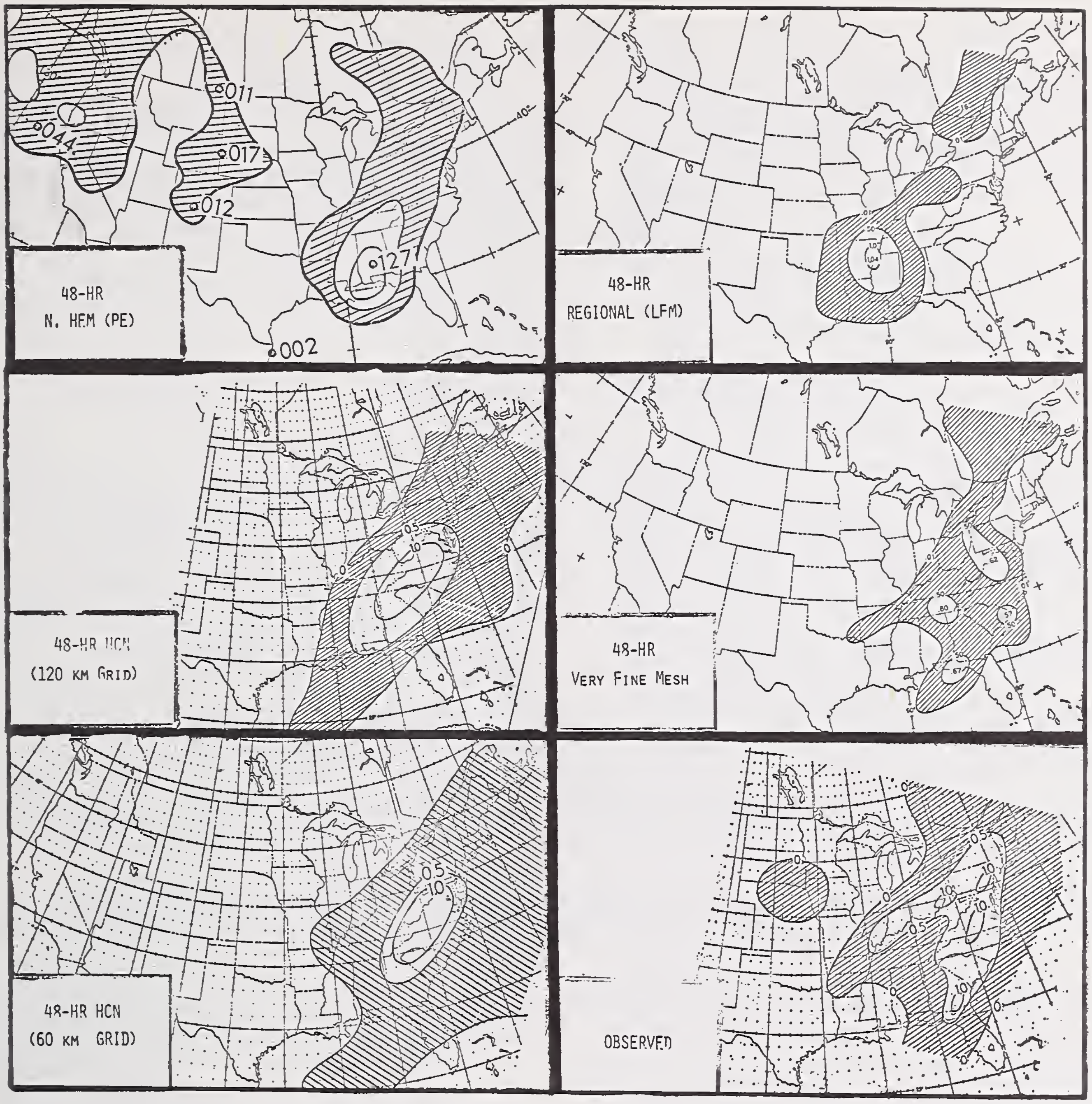


Figure 7.--Forty-eight hour forecasts of 12-hour precipitation from 0000 to 1200 GMT on 26 December 1975 made by 5 NMC operational and experiment models. The observed precipitation is in the lowest right-hand panel.

Several experiments have been run at NMC to find out what benefits can be realized from using finer-mesh models, particularly in precipitation forecasting. Figure 7 illustrates the results of one of these experiments: a 48-hour forecast of precipitation with last year's Christmas storm. This storm moved from the Gulf of Mexico northward to the Ohio Valley, deepened and produced significant precipitation both east and west of the Appalachians, as shown in the lowest right-hand panel of figure 7. Each of the 5 models used in this experiment are similar in basic structure; the main difference is in the size of the grid used in each model. Note that the location of the heaviest precipitation area improves with each succeeding finer-mesh forecast beginning in the upper-left panel of the figure. This and other similar experiments indicate that use of a finer mesh increases the skill of the model in locating the area of heaviest synoptic-scale precipitation. Even the 60 km Hurricane model did not successfully forecast the smaller-scale detail in the precipitation pattern east of the Appalachians.

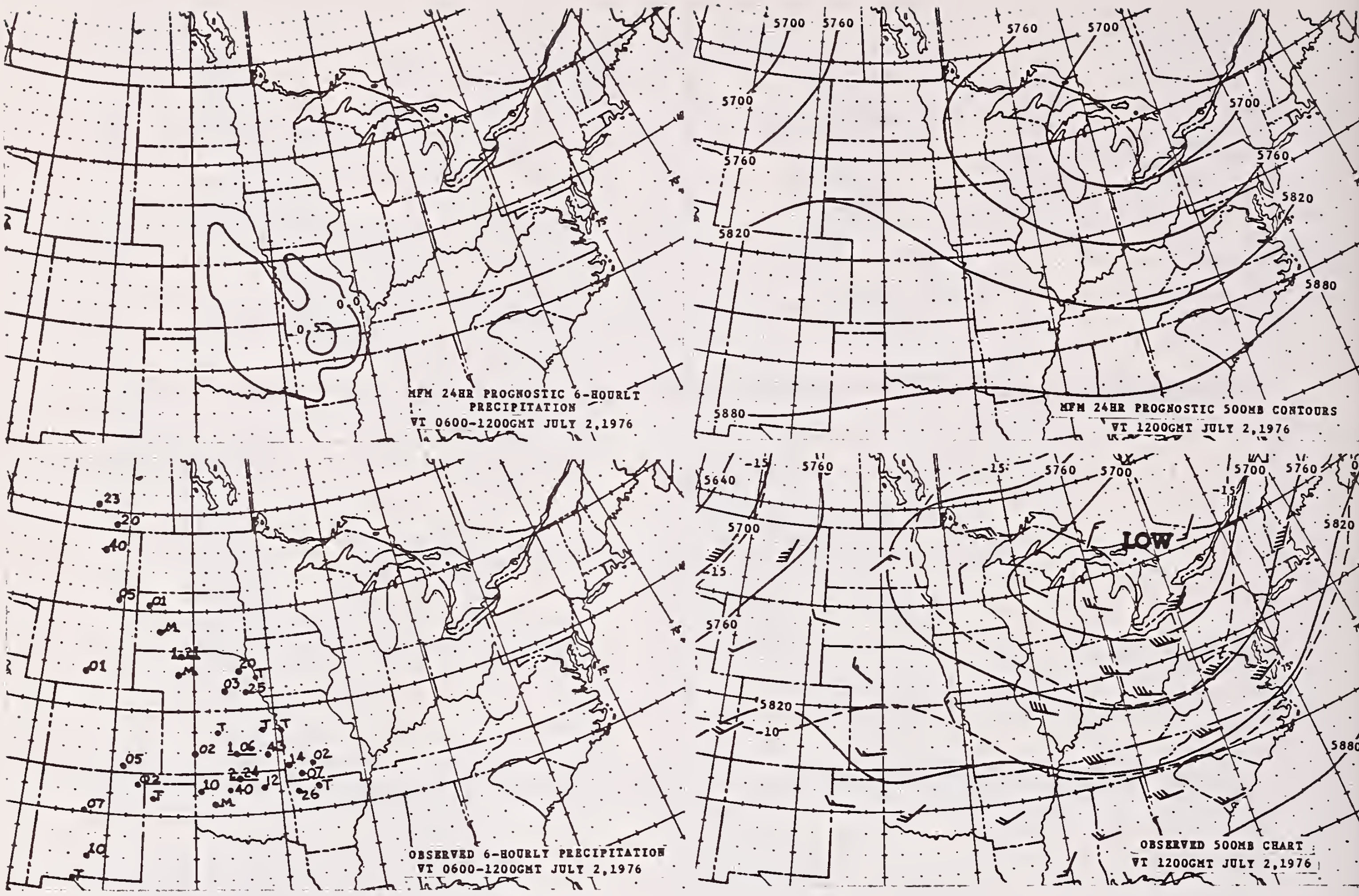


Figure 8.--Twenty-Four hour forecast of 6-hourly precipitation and 500-mb contours made by NMC's Movable Fine Mesh (Hurricane) model (top diagrams) and verification (bottom diagrams)

Experiments run with the 60 km Hurricane model on warm season situations tend to confirm that the model is not forecasting small-scale precipitation. Figure 8 illustrates this for a situation last July in which heavy convective precipitation occurred in the central Great Plains. The model underforecast the amounts of precipitation and located the area too far east. In fairness to the Hurricane model, it should be stated that both the hemispheric P.E. and regional LFM were unsuccessful in this case. Also, the current version of the Hurricane model does not provide for the diurnal heating cycle and has a convective scheme oriented toward maritime tropical conditions in contrast to the two larger mesh operational models.

CONCLUSIONS

Current capabilities in use of numerical prediction for forecasting can be summarized as follows:

- Significant progress has been made in the past 10 to 15 years in the forecasting by numerical methods of synoptic-scale weather features and of weather parameters which can be derived from them.

- The progress in forecasting precipitation and other small-scale weather elements has been very small.

- Finer-mesh numerical models already show some skill in improving forecasts of the location of precipitation areas and precipitation amounts.

- Important problems remain to be solved in the application of numerical techniques to the forecasting of smaller-scale weather phenomena, such as thunderstorms and heavy precipitation.

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Review of Operational Forecasting[1]

William G. 'Sullivan[2]/

A short review and discussion of operational fire weather forecasting from a field forecaster's point of view. Forecast problems, accuracy, and limitations imposed on the forecaster are discussed.

INTRODUCTION

Fire weather forecasting service has been available to land managers for many years but it was not until 1960 that an organized expansion plan was formulated and services increased throughout the country. Additional fire weather forecasters were assigned to many existing offices and new programs were established in areas where none had existed prior to that time. There was little change in the program from 1965 to the early 1970s as the new and increased programs were being developed. In the early 1970s a major forecast program reorganization was undertaken in the National Weather Service which affected some fire weather program services.

During this same period of time many changes occurred in the approach to forecasting itself. These changes were the result of new technology such as improved numerical modeling, satellite data, radar, and improved communications equipment.

The purpose of this paper is to discuss the present state of the art of fire weather forecasting in light of these changes and the impact of these changes on the fire weather programs and services.

1/Paper presented at Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.

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FIRE WEATHER FORECASTS

In talking to fire weather users one often gains the impression that they think there is something basically different between fire weather forecasters and forecasters making other types of forecasts. This apparently stems from the user's failure to make the distinction between forecasting and services. They have a tendency to focus on the fire weather program as a whole. In this context you will often find that a user's opinion of the forecasts depends not so much on the quality of the forecasts as the personal relationship that exists between the user and the fire weather forecaster. One is not quick to critize one's friends. On the other hand you will sometimes find the user's opinion of the forecasts to be quite low due to a lack of close working relationship between the user and the forecaster when, in fact, the forecasts are well up to the state of the art.

Fire weather forecasting per se, does not differ markedly from any other type of forecasting. We are trying to get from here (initial conditions) to there (conditions at some future time). Fire weather forecasters approach this task in the same manner as any other forecaster using the same basic tools and information.

The starting point for all forecasters is the basic quidance material disseminated by the National Meteorological Center (NMC) in the form of prognostic charts generated by the various numerical models in use by

the National Weather Service. During the past few years there has also been an increasing amount of objective guidance material obtained from statistical output of the numerical models (MOS). This output provides direct forecasts of temperature, probability of precipitation, wind, cloud cover, and other information not directly related to land manager's use. At the present time the MOS forecasts are provided only for cities but are useful in some fire weather areas through interpolation.

From a forecaster's point of view there has been a marked improvement in the operational numerical models in the past 10 years. This stems not only from more advanced models but from increased observational input such as that obtained from satellites over ocean areas. Evidence of this can be seen in a trend away from the development of local objective forecast schemes using observed data in favor of methods using input derived from the models. There has also been a trend toward using subjective evaluation of the model progs in place of some of the older objective systems. An older objective system for forecasting Santa Ana winds is a good example. Once the basic mechanism for the development of these winds were better understood, the improved numerical progs give a more reliable forecast than the objective system.

From the point of objective guidance received from the NMC the forecaster then goes to an almost purely subjective routine. Many offices have one or two local objective forecast systems to aid in the process but few, if any, use a system without subjective adaptation. The subjective process is an individual thing with forecasters but I like to think of it as a kind of mental modeling. In simplified terms, the forecaster models the current weather conditions with the current synoptic scale flow pattern and makes changes to these conditions as indicated by the progs and other guidance material using his or her skill in recognizing influences not known to the models. Where the state of the art ends and pure conjecture begins, I do not know.

Forecast Accuracy

In spite of the improvements in numerical modeling and additional data in former sparse data areas there has been only a small increase in accuracy of the day-to-day forecasts as shown by verification statistics. This can be misleading, however, because the major effort in forecast improvement over the years has been in the forecast and dissemination of warnings of severe weather conditions and we have seen substantial improvement in this area.

The paradox of improved synoptic scale models with little increase in forecast accuracy stems mainly from the fact that it is a very long step from the synoptic scale progs to the weather forecast. Better progs permit the forecaster to start from a more sound base but local weather changes are most often the result of sub-synoptic scale systems, interaction between the flow and terrain, heat sources and sinks, and other energy exchanges either not handled well or not known to the model. A number of efforts have been, and are being, made to model the sub-synoptic scale in both predictive and diagnostic approaches and one could reasonably expect some increase in forecast accuracy from the results. Experience has taught us, however, that improvements occur in small increments and there is nothing to indicate that this will change.

Forecast Verification

It is always a risk to make statements about the accuracy of forecasts without supporting facts but verification data on fire weather forecasts are not all that abundant. There is no standard verification system for fire weather forecasts but most offices maintain some type of informal system as a check on their forecasts. Experience has taught us that verification is an important motivation in forecasting as well as in many other endeavors.

Those verification statistics that are available show average errors of 2 to 3 mph in wind speed and 5 to 8 percent in relative humidity forecasts. Errors in relative humidity are slightly larger in the northwest and eastern parts of the country. This is probably due to the higher average humidity in those areas rather than a difference in skill since errors are largest during periods of high humidity in all areas.

Some offices elect to verify one or more of the fire danger indices rather than weather elements but I believe this is falling into the same trap that users often do, i.e., looking upon NFDRS indices in absolute terms. It makes little sense to verify a weather forecast using some measure that includes input other than weather. I say this with the full knowledge that I have done the same thing in the past. Most of the indices in the NFDRS include the fuel

complex whose input is represented in a relatively crude sense.

Lynott and Graham (1973) made a comprehensive study of fire weather forecast verification for Washington and Oregon. Since they were studying an area with well established fire weather programs, in an area with a wide variety of weather and, for the most part, a group of experienced forecasters this study probably gives a good representative measure of fire weather forecasts for much of the country. The study included forecasts issued at six fire weather offices for both the morning and afternoon presuppression forecasts, although only the results of the 24-hour forecasts issued in the afternoon will be discussed here.

The results show that for the six stations the average error in humidity was less than 10 percent 67 percent of the time. The forecast wind speed error was less than 4 mph less than 83 percent of the time. These figures appear comparable to the average errors mentioned previously. I think it is safe to assume from this that the study is, on the whole, valid and probably represents the field forecasting level of the state of the art. Going further, the study also makes a distinction between the total number of forecasts verified and those cases where a large change occurred in the weather element. A large change was arbitrarily defined as a change greater than 9 percent humidity and greater than 3 mph in wind speed. A large change in humidity occurred in 36 percent of the cases and in wind speed 32 percent of the time. Of the cases with large changes the forecast humidity error was 9 percent or less 49 percent of the time and the wind speed error 4 mph or less 68 percent of the time.

Contrary to the conclusions indicated by the authors the results of their study show the forecasts to have a fairly high degree of usefulness in fire management. If we consider the magnitude of the forecast errors in the context of the NFDRS, for which these forecasts are intended, the value of the forecasts increases significantly. A change of 9 percent in relative humidity is roughly equivalent to a change of 1 percent in the fine fuel moisture. The error in wind speed has a much larger effect on the NFDRS but part of this effect is in the design of the system. If you allow the spread component to vary between 0 and 100 while restricting the wind speed to a range of 0 to 30 you are going to get large changes in the spread component with relatively small changes in wind speed.

We have no verification statistics for fire weather forecasts for other than presuppression forecasts, but since we continue to get a large number of requests for forecasts for going fires and prescribed burns it is safe to assume that these types of forecasts are very useful to land managers.

Limiting Factors

There are a number of factors that affect the accuracy of the forecasts that can be identified. The most important can be referred to as the fundamental limits imposed on the forecasts such as inadequate sampling of the atmosphere, imperfect modeling, and variations of the weather that are caused by sub-synoptic scale systems. These are limits imposed by the state of the art and are likely to remain with us for a long time to come. However, it is not necessary that these limits be eliminated in order to improve the accuracy of the forecasts. When we speak of inadequate sampling or imperfect models we do so in a relative sense. Perfection in either of these is probably unattainable but as we improve on the present state of the art we can expect some eventual improvement in the forecasts.

Ironically, one important factor that affects the forecasts is the unnecessary limits imposed on the forecaster by the users. This includes the time consuming job of preparing basically the same forecast in many different formats for the different users. The NFDRS in use by some of the larger fire control agencies requires a rather precise standard forecast format. There are many agencies throughout the country whose fire suppression programs do not require a system this sophisticated and therefore require forecasts in a variety of formats and sizes. Any time taken from the forecaster for this type of work is time that is not available in the formulation of the forecast. In addition, this work detracts greatly from the forecast during those periods of time when the fire weather specialist is not on duty and the forecasts are made by other forecasters. The decrease in quality of the forecast stems from other forecasters getting bogged down in detail rather than any difference in skill.

Other limits included in this are the requirement that forecasts be valid at a point in time rather than for average conditions, poor quality of observations, no observations at all in some areas during fire situations, and last but not least, AFFIRMS.

The problems with AFFIRMS has not changed significantly since it was reported on by Sullivan (1974). The main problem for the forecaster with AFFIRMS lies with the restrictions in the way forecasts can be entered. On the one hand it is desirable to keep the computer program small for economic reasons while on the other the forecaster needs to be able to enter precisely the forecast he wants for each station. Without this ability the accuracy of the forecast will suffer. During the 1975 fire season, WSFO Los Angeles, discontinued the routine practice of making special forecasts commands to overcome observational errors or nonrepresentative observations due to temporal variations in the weather. Our forecast error promptly increased but we have continued the policy anyway. At least one fire weather office in the west has discontinued their verification program because of these problems with the ZONE command in the AFFIRMS program.

Forecast Application

The limits on the accuracy of the forecasts notwithstanding, there is much value in the forecasts. How much value depends not only on the forecast but also the manner in which it is used. On the whole, it has been my experience that users expect more of the forecasts than it is possible for the forecaster to give and utilize very poorly that which is available. This may sound harsh but it is not meant to be. It is simply an observation whose validity can easily be shown but which I will not go into here. That it may be true, however, has and is being increasingly recognized by people concerned with this problem.

Two meetings held earlier in the year on the west coast discussed weather needs for fire and wildland managers. It was brought out in both meetings that weather information presently available could be better utilized. The second meeting, in touching on this subject, pointed out that meteorological results are transferred to people who are neither academically nor occupationally trained in meteorology. Actually, for most meteorological applications, the technology gap occurs a little further down the line. Meteorological research results are normally transferred to the forecasters who in turn pass the acquired knowledge to users as operational information. There are some climatological applications, of course, that can be passed directly to the user.

A large technology gap does exist, however, between the forecaster and fire and wildland user groups that prevents maximum utilization of weather information. It is not the local manager's fault because obviously people would prefer to be completely knowledgeable about whatever they have to do. We have taught fire managers some very elementary meteorology in fire schools, and somewhere along the way some have gained the impression that these people have a knowledge of meteorology sufficient for a wide range of applications. I do not think we will bridge this gap between forecast information and user application at the field level until applications people, academically and occupationally trained in meteorology, are included as a part of the user organization. This is especially true where the application of weather information is required in complicated and sophisticated land managements systems such as the NFDRS.

FIRE WEATHER SERVICES

The NWS fire weather program provides a number of services in addition to the forecast program. The forecast reorganization of the NWS had some impact on these services but it is difficult to determine the exact extent because of several other factors that have also occurred in the past few years.

From my own personal experience, committments to other NWS programs imposed on the fire weather forecasters did not, in themselves, restrict or decrease the service provided to fire and wildland user agencies. What it, and other work schedule committments, did was to limit the instant accessibility of the fire weather forecaster by the users. The solution to this problem is better planning on the local level in connection with those services other than forecasts, such as consultation, training, etc.

Mobile Units

Fire weather mobile units manned by a fire weather forecaster are available for large going fires and prescribed burns throughout most of the western states. Coverage is quite extensive and units are moved from district to district when required during large and multiple fire situations. These units have proved invaluable in the west where terrain influences on the weather are very large. The mobile units are replaced and equipment

upgraded from time to time to maintain their effectiveness.

Consultation With Users

Another service provided over the years has been local consultation with users on fire and wildland management problems. A great deal of the application of weather information during the past has been accomplished on the local level by the forecaster and user. This is one of the more personalized services provided over the years, but rarely has this phase of fire and wildland management been exploited to its fullest potential because of its dependence on personal relations, lack of organized program and direction, and time limitations on both sides.

Training

Fire weather forecasters serve as instructors at fire behavior schools at the request of various fire control agencies. They have also been of great help in formulating standard training courses for the U.S. Forest Service and Bureau of Land Management. Most training schools are planned far in advance so the fire weather forecaster usually has no difficulty in eliminating conflicts with other program committments when requested to participate. Some local fire school participation is still requested on relatively short notice, however, and more advanced planning with the forecaster will be required in these cases.

Weather Station Inspection

This service has consumed a good portion of the forecaster's time during the pre-fire season, however, during the past few years this has been drastically reduced due to budgetary restrictions. From a personal standpoint I think this is a case where evolution in the program would have accomplished the same effect. The location, installation, and routine inspection of fire weather stations can easily be handled by user personnel with a small amount of training.

SUMMARY

The NWS provides fire weather services over a wide range of activities with the main one being the extensive fire weather forecasts for fire and wildland management.

The forecasts are, in general, well up to the state of the art and provide a useful and necessary service to user agencies. The forecasts contain technical information valuable to the users but which require more technological knowledge within the user agency to obtain the full benefit of this information.

There are certain limiting factors that affect the accuracy of the forecasts, some of which are imposed by the state of the art and whose effects can only be reduced slowly. Other limiting factors are often the result of user demands and application, and can be reduced significantly with a minimum of effort. Research is needed in all areas but a strong research program directed toward applications offers the quickest rewards.

Effects of the NWS forecast reorganization has had some effect on services but they are difficult to define. Where adverse effects have occurred they should be examined and solutions sought.

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A Review of National Weather Service Policy on Services[1]

Gerald A. Petersen[2]

Abstract--The basic National Weather Service policy on services is still to meet the objectives of the service programs by the most efficient use of resources and technology. The present operational policy is to concentrate our professional talent in large Weather Service Forecast Offices.

The National Weather Service has a history of serving the needs of forestry that extends back to 1913. During this 63 year period, advances in technology, the state of the art, availability of professional staffing stated needs of forestry weather users, and the vagaries of budgets have caused many changes in the way we have provided forestry weather services. Over the years, our policy has been to meet the objectives of the Fire Weather Program by the most efficient utilization of available resources and technology; and to insure that any changes in our operating procedures did not degrade the service level. Our present method of meeting program objectives makes use of the facilities and staffs of our larger offices to provide the required fire weather service. These larger offices, termed Weather Service Forecast Offices, have relatively large professional staffs and are the first to receive new technological equipment. By concentrating forecasters and equipment in 52 Forecast Offices, we can make the best use of professional talent, modern technology and the state of the art advances to meet the weather support requirements of all of our "customers." Over half of our Forecast Offices do have an extra forecaster assigned to the staff as a Fire Weather Focal Point; the remainder of the Forecast Offices use their regular staff to provide their assigned Fire Weather Services.

In addition to the Fire Weather support provided by the Forecast Offices, 15 smaller Weather Service Offices, mainly in the Western U. S., are especially staffed to provide Fire Weather Service. In the Far West, on-site support also is provided by mobil fire weather units.

Of course, local forecasts and advisories on local weather conditions are available to Forestry interests at most of our 249 Weather Service Offices throughout the country.

One aspect of the present NWS Special Program operation that has raised "problems" among some of our old-line forecasters as well as among some of our "customers", is what we call the Focal Point/cross-utilization concept and what some of you term the "Problem of the Faceless Forecaster." NWS implemented cross-utilization to meet the tremendous and ever-increasing need for weather services of all types. In the case of Forestry weather, expanded, sophisticated land management and fire suppression operations have vastly increased the demand for special weather support. This demand has grown to the point where, in most cases, a single meteorologist in an office, working 8 hours per day, 5 days a week, 48 weeks a year cannot possibly satisfy the need. In our view, the most efficient way to meet the operational weather needs of forestry interests is to cross-utilize our forecasters and tap the abilities of several "Faceless Forecasters."

This "Faceless Forecaster Problem" is really psychological and should have no real impact upon the quality of our operational services. Once the special program user--in this case the forestry community--recognizes that trust can be placed in this different mode of operation, the psychological impact will diminish. The "faceless forecaster" has long been serving the needs of public weather, flood forecasting, and severe weather warning, as well as many other specialized interests such as those involving aviation, marine shipping, and recreation. So long as our forecasters are kept aware of the weather needs of the forestry interest, we are sure that we can fulfill the important requirements of operational forestry weather support. And that really is one of the reasons why we have meetings of this type from time to time.

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One of our greatest problems with cross-utilization is dealing with misconceptions of what cross-utilization does. One common misconception is: "Under cross-utilization, there's no fire weather support available from an office when the fire weather man is working different shifts." This simply is not true; other members of that office's forecast staff can and do provide operational fire weather support. In fact, cross-utilization provides the depth of manpower to provide those important operational services on an around-the-clock, 7 day a week basis if needed, regardless of sickness or health, days off, or vacation plans of any one man.

Another misconception is: "cross-utilization has replaced trained fire weather forecasters with untrained ones." This is really a half-misconception. Trained fire weather forecasters have been replaced with untrained fire weather focal points, but this is not the fault of cross-utilization; it would have happened no matter what. Our trained people retired or were promoted to other jobs. We are now taking steps to develop training plans for the fire weather, agriculture, and marine programs. A small beginning was made this past September when we sponsored two consecutive seminars for our Eastern fire weather focal points.

All in all, the cross-utilization concept does provide more depth to our services, especially to the special program forecast services and does permit greater opportunity for career development to the Special Program meteorologist.

For those of you who yearn for the "Good Old Days", a study of Fire Weather Forecast verification in 1929 found that the second period Relative Humidity forecasts were so bad that it was recommended that that part of the forecast be dropped. Since that time I believe we have been able to make at least some improvement in the second period forecast.

While our 1929 Forecaster was plagued with sparsity of information and spent much of his time trying to figure out what was happening, our modern forecaster may, at times, be overwhelmed with data, information, and guidance, but he does spend most of his time working on the forecast problem.

To produce the products to meet the requirements of the Fire Weather Program, our forecasters have the following material available on a 24-hour, 7 day a week basis:

- Extensive forecast guidance material from the National Meteorological Center, produced by both computer and man. While the NMC products may not be specifically designed for Fire Weather, they can be adapted for Forestry Weather use.

- Plotted and analyzed charts. Forecasters only do minor supplemental plotting and analysis.

- Data from several observational networks. This data includes hourly surface weather and radar reports along with upper air observations.

- Satellite photos and interpretive discussions. All Forecast offices do receive photos of their area as frequently as every 30 minutes on a day and night basis. Special satellite photo interpretations are provided for our forecasters from Satellite Field Service stations at Miami, Washington, Kansas City, and San Francisco.

Soon the forecaster may have even more NWS resources to draw upon. The NWS and the U. S. Forest Service are exploring the feasibility of adding a forestry weather function to our Environmental Study Service Centers. An E.S.S.C. forestry operation could support our fire weather forecasters by acting as a liason between the user and producer, by identifying problem areas, and by providing specialized weather products that would supplement our regular forestry weather forecasts.

So much for the present operations of the Forestry Weather program. What's the outlook for NWS Special Program Services over the next 5 to 10 years? Frankly, we can't ever be too sure. However, after the turbulence resulting from the implementation of AUTOMATED FIELD OPERATIONS AND SERVICES (AFOS) program subsides and new automated data handling support become operational, we believe more forecaster time and attention will be available for all of the Special Programs. We don't really see any major changes in the National Weather Service policy for Forestry Weather Services. Simply stated, "The NWS will do what it does best to help Forestry interests to do what they do best."

Adaptation of Meteorological Products for Specific Forestry Uses[1]

Paul E. Krauss[2]/

ABSTRACT--A brief review of the primary uses of meteorological products by the forest protection organizations in the Pacific Northwest. This information relates closely to the activities and responsibilities of the Department of Natural Resources in the State of Washington and its use of meteorological information.

The title of this assignment has bothered me! Adaption seems to say I have purchased a new shelf item which I must now find a way to fit to my needs. I am sure the subject heading was not intended to imply such a feeling, but I think it states very well an underlying problem today. In explaining my concern I will need to talk for a few minutes about the forest manager, one of the users.

The forest manager is requesting, yes, shouting for help. He is in a fixed location with specific acreage to manage primarily for the production of a wood product. He is faced with environmental problems imposed by nature itself and recently magnified by public concern to a point where his daily activities are monitored by the public. He must protect such things as air quality, water quality, aesthetics, soil productivity and the resource values he intends to market. He needs to know what's going to happen on his acreage today while he is engaged in executing his planned management program. He must know what impact that activity will have on the environment this evening, tomorrow, next month, next fall, and the years to come. Meteorology is a science! How often have you also heard or said that scientists talk among themselves? Now you're saying to yourself, ah ha--but he is wrong about meteorologists. But am I?

Meteorologists have used acronyms for a long time and these have quickly found their way, mixed with others relating to the forest managers' interests, into the current topics until they sound like the title to foreign manuscripts. The forest manager gets information from NOAA, OSHA, WISHA, FOCUS, BIFC, AFFIRMS, NFDRS, and FIRESCOPE to name those in use on the West Coast. Meteorological information is transmitted by radio, telephone, teletype and computer and in that process is supposed to be decoded for the simplest of uses. The user gets a narrative which includes words intended to aid in the explanation such as diffusion, dispersion, inversion, stable, unstable, 500 and 800 millibar, intermittent, marine push, and thermal trough.

We have a meteorological research group in the Pacific Northwest who are quick to state that meteorological research up to 1969 was phenomena-oriented to such subjects as low level jet stream, sea breeze, smog transport, etc. Now it is to be expanded to solving problems for the western forest user in all aspects of forest meteorology. A word of caution, are these researchers agreeing among themselves again? The object of producing a product is to have it be sellable. Researchers must satisfy a need. In the Northwest the response by users or potential users to the inquiries by researchers has not been one of overwhelming enthusiasm. We must not ignore the replies that indicate the first priority is to be able to use what is available, or to understand the present state of the art.

Let us look at another type of research being applied by the forest manager. Silvicultural research people are conducting research for people practicing silviculture. The recipients of the research are persons who have been academically, as well as occupationally trained in silviculture. Contrast that with the background of the meteorologist doing meteorological research and the forester engaged in forest management. I think there is a technology gap that may be much wider between the meteorologist and the forest manager than that of which we are aware or wish to acknowledge and it can quickly expand from the present threshold. I want to illuminate that point because I think we all need to work toward the elimination or prevention of a technology gap. We must make sure the research results are made operational. We have already

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heard today about some of the needs of the user and the capabilities of the producer. Let's be sure that the capabilities and the research objectives initiated to satisfy the new needs are put together in a manner that will satisfy operational usefulness. Let's not produce a shelf item which requires some adaption by the user. Egotism has sometimes been defined as that certain something that makes a person in a rut think he is in a groove. Don't outrun your user. Accelerating technology is creating more variables than existed before. Are the intended users ready for the change? Good personnel management techniques must be applied by the user. It's too easy to say, "If you're so clever, why don't you give me some answers?" Currently meteorologists do give the user a minimum of a 24-hour glimpse into the future. Yet many recipients still wait until tomorrow to plan the day. Why? What is the nature of your audience? Think of other prefessions and their reaction if they could see tomorrow's paper 24 hours in advance. An investor would have difficulty waiting for the stock market to open. Personnel problems would be prevented. Production would be at maximum capacity. We involved in forest management must reassess our use of the available meteorological information and perhaps more important, we must clearly identify the needs not yet answered.

Well, what are the forest managers in the Northwest doing to utilize the present products of meteorology? I earlier said that the manager is interested in producing a wood product that is sellable. You are all aware of the success of the timber industry in the Northwest, but this action produces a by-product--slash, which has no market and presents a fire hazard as well as a problem in getting the land back into production. The forest manager prescribes a method of removal or reduction of the slash to solve these problems. Prescribed burning is often the solution. Imagine for a moment the concerns of escaped fire and damages to the soil which might occur if you choose the wrong time to burn an accumulation of up to 150 tons per acre of slash within the confines of the forest. This decision to burn requires a careful study of known and predicted weather. Fuel moisture, the amount of moisture in dead wood is recorded for days since it is somewhat progressive and responds to rainfall and drying, either by sun or wind. Fuel moisture in the adjacent forest cover is studied to be sure a fire won't race through your natural barrier. Slope, aspect, elevation and geographical location are provided the fire weather forecaster. Readings of wind speed and its direction, temperature and humidity at specific times are also noted and a spot forecast is made for the location. This forecast is the major tool used in the final decision to ignite. The 24 hour glimpse into the future has been used in the management decision.

Both the State of Oregon and the State of Washington have a smoke management program. This program is utilized to insure proper dispersal of smoke from, not only the prescribed burning, but for all the smoke occurring from forest land activities. The plan requires that all smoke gets above a 2,000 foot elevation over designated population densities and further it must meet the requirements of the Department of Ecology in the State of Washington who has the responsibility for carrying out the requirements of the Clean Air Act. Although this may not be a tool used by the forest manager, it is certainly a restraint under which he must daily do business. A smoke management forecast is required by the user.

In the State of Washington, the smoke management program is administered by the Department of Natural Resources. We request a prediction of wind activity at the 3,000 foot and 5,000 foot elevations. We need to know if it is stable or moving and its direction and speed. We plot the predicted routes of the smoke, and we know that it will travel 60 to 100 miles at a minimum. We study the fluctuations in temperature predicted for the day. Smoke rises higher with rapid heating. It correspondingly falls quicker on a cool day. If it appears that it will travel over designated areas, at too low an elevation, we inform the user that he cannot ignite due to smoke management problems.

The method of ignition is very important in reaching the decision to burn. We, involved in prescribed burning in the Northwest are using mass ignition techniques such as explosives to literally shoot the smoke to the desired altitudes for proper dispersal. In the past two years the logging industry and the Department have had considerable success by using a helicopter and a large drip torch suspended beneath the aircraft for quick ignition. I know of one instance this summer where 300 acres were ignited in 26 minutes by the use of two helicopters lighting in strips approximately 30 feet in width. This rapid ignition creates its own firestorm and the resulting draft drives the smoke to the desired elevation. The forest land manager is also becoming concerned about visibility and who will see the smoke. As a user, he needs to know more about smoke dispersal and where it might accumulate. Accumulation seems to varry from drainage to drainage. We need to have predictions for some of the major drain-

ages in the State of Washington.

Weather Forecasters are utilized in compiling the severity of our forest fire danger. The forecasts of weather combined with the National Fire Danger Rating System (NRDRS) provides us with the predicted fire danger level. The information predicted for temperature, humidity, preciptiation, wind direction and wind speed are entered into the NRDRS, which generates some useful components and indexes when combined with a fuel type and slope. A few of the components of fire danger and indexes available are ones that predict the rate of spread, the probability of ignition, the resistance to control and the energy release. Each forest protection unit's daily activities are based upon the predicted fire danger. The strength of force for the next day for fire suppression and detection techniques are an indirect result of the fire weather forcast. For example, the ignition component is used directly for our air detection flights over the eight million acres of land we protect in Western Washington. The number of air detection flights per day and the time of the flights change from day to day as the predicted probability of ignition changes. The variation is from no flights to a maximum of three airplanes in the air on each of the six preplanned flight paths.

This same information, the prediction of the fire severity, is also reviewed in considering the implementation of regulatory measures for forest users. In the State of Washington, and Oregon has simular statutes, we have the authority to partially restrict the industrial user to periods of the day in which he can utilize power driven spark emitting equipment to a point of total restriction or shutdown. Another user, the recreationist can also be restricted by a simular procedure. In that action a forest closure is enacted. In both considerations the mathematical probability of a fire starting, its predicted rate of spread and resistence to control in specific fuel modules are extracted from the known weather and the known action of fire in the fuels being considered are the tools used in making the decision. This provides us with a means of regulation in a specific weather zone or zones without involving the remainder of the state.

In the event of an extra period fire, the fire weather information is utilized in planning fire suppression strategy. This type of fire becomes a idenity of its own, requiring foreacting for its specific geographical conditions and fuels. Moble weather stations are utilized and we immediately build useful data to aid in both mobilization of forces necessary for suppression and when that need is satisfied, a orderly demobilization plan is enacted from the continuing weather data.

The State of Washington has over 13,500 bits of weather information computerized for the year of 1975 on nine different weather zones. This information will lend itself to every kind of analaysis desired in comparring predicted weather to actual and predicted manning schedules to what actually was used to further increase the creditability of fire planning for all types of forest activities and certainly for fire suppression needs. I have a real interest in the program of combining the computerized weather information with the fuel type, its density and age, the drought condition, the slope, elevation, aspect and other conditions of the fuel and topography to predict by map printout the progress of a known fire by time periods of the day if suppression action is taken. Not only would this be vital and useable tool in suppression work, but it would be a factor in determining which fire to take first action on in a multiple fire situation such as those resulting from a widely dispersed lightning storm. We utilize the weather data as a triggering device for fire prevention news and educational releases to the media. Many summer days on the west coast begin with overcast skies due to the marine flow of air from the coast. This lulls the citizen into a false sense of security as cool air, something you feel, is a poor indicator of the possible conditions of the forest fuels.

In Washington, our department has a working arrangement with the logging industry and other users of aerial photos by which the department contracts the aerial photography flights on a regular agreed time table and all users pay a use fee for photos used. We not only use the weather predictions for clarity of day since clouds cast shadows on the forest canopy and prevent clear photography but we also study the measured snow pack, which by reflection can overexpose the photo. Clear, shadowfree, nonglare aerial photography is the result of good weather information.

Wind direction and intensity is carefully reviewed for aerial spraying and fertilization contracts. You may have heard about the Spruce Budworn infestation in the western states, particularly Washington. Once agreement had been reached to spray, the spray had to be applied during the larva stage which is something less than 4 weeks. The progress from egg to larva is determined by the increase in temperature of the habitat area as we progressed from spring to summer. This narrow band of time was further restricted by the constraints involved in the use of aircraft. The daily

wind direction and intensity has a direct effect on the success of any spray application. The application of Dinitro, a chemical utilized to brown or dehydrate the folage of broad leaf species so that it might be burned by prescription is done by utilizing the prediction for moisture free days along with the intensity and direction of wind for accurate spot application. The fact that you may want to rid your stand of broad leaf species for the purpose of propagating a coniferous forest may not be true of your neighbor, who is more interested in aesthetics. We need more weather information for spot locations for fertilization, dormat and foliar spray and aerial seeding. Wind draft is the most feared possibility. Night flying of helicopters by use of night vision goggles is a probability in the near future. Small drone aircraft are on the list of products available for the forest user to scan or oversee activities in the forest. Both of these uses will put an added demand on weather needs in the form of predicted air temperature, air densities, wind direction and intensity!

In land management work, forest landowners have just scratched the surface in utilizing daily weather as a factor in work planning. I have explained the uses primarily related to fire activities and aerial work. Consider tree planting where one can utilize the knowledge of frost level information, freezing elevations and snow cover as well as knowledge of drying winds. We have begun to utilize weather forecasts to predict rain occurrance and intensity when involved in a road paving and oiling projects. After completion, we utilize it as a "Road Resource" alert when knowledge of heavy rains is predicted. This involves culvert patrol for cleanout and the placing of visqueen on recent cuts and fills to prevent damage and erosion. When aircraft are involved for the transportation link for V.P. tours, we again run to the forecast.

I think I should close with the recommendation that users and producers consider a "dial-a-forecast" for the future for the specific area of concern. Computerized output for a specific geographical unit predicted from a continuous input from automated weather stations is the desire. That ladies and gentlemen is the utopia the user desires for his acre today.

A Lightning Direction-Finding System for Forest Fire Detection[1]

R. C. Noggle and E. P. Krider[2]/

D. L. Vance and K. B. Barker[3]/

Abstract.--A new type of lightning direction-finding system is described which detects primarily discharges to ground and which discriminates against intracloud discharges and background noise. Ground discharges are selected by requiring the wideband magnetic waveforms to have rise times, widths, and multiple peaks characteristic of return strokes. Other signals are rejected if they do not have the proper shape. Accurate azimuths are obtained by sampling the magnetic field just after the initial radiation field peak. Tests in Alaska and Arizona indicate the system accepts return strokes with efficiencies ranging from 70 to 90% and rejects 97% or more of the improper waveforms. Six systems have been operated in interior Alaska by non-technical personnel and have provided significant aid in the detection of lightning-caused fires.

INTRODUCTION

Each year lightning starts approximately 10,000 forest fires in the United States. The lightning fire hazard is particularly serious in remote areas, such as interior Alaska, because of the greater difficulty in detecting such fires quickly. Meteorological satellites and weather radars can identify convective cloud systems and precipitation, but not lightning. Large clouds may produce much precipitation and little lightning, and small clouds may produce much lightning and little precipitation. Clearly, an inexpensive electronic system which can automatically detect and locate lightning, particularly discharges to ground, over rather large areas with good accuracy would be a valuable aid to both fire management and fire weather personnel.

We should recall that a typical lightning discharge to ground or *flash* is made up of several component *strokes* (Uman 1969). A flash starts with a faint leader which proceeds rather slowly from cloud to ground in a series of short luminous steps. After this *stepped leader* contacts the ground, a very energetic and bright *return stroke* propagates up the ionized path established by the leader. After a pause of 30-50 milliseconds, a new leader, the *dart leader*, proceeds uniformly from cloud to ground and is followed by another bright return stroke propagating rapidly upward. A typical flash is made up of 3 or 4 leader-return stroke combinations. Return strokes have large peak currents, typically 20,000-40,000 amperes, which rise from zero to peak in just one or two millionths of a second while the strokes are still close to the ground.

In this note, we describe a new type of lightning direction-finding system which senses the magnetic fields which are produced by the large return-stroke currents. The system selects ground discharges by requiring

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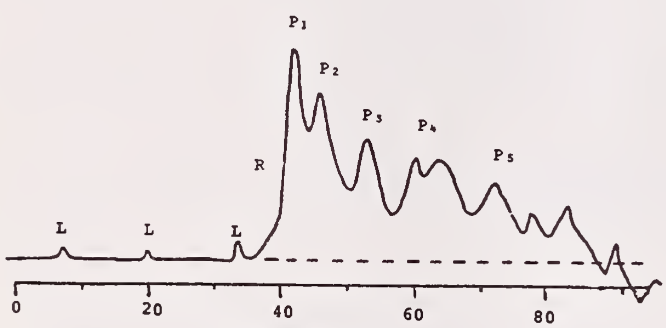
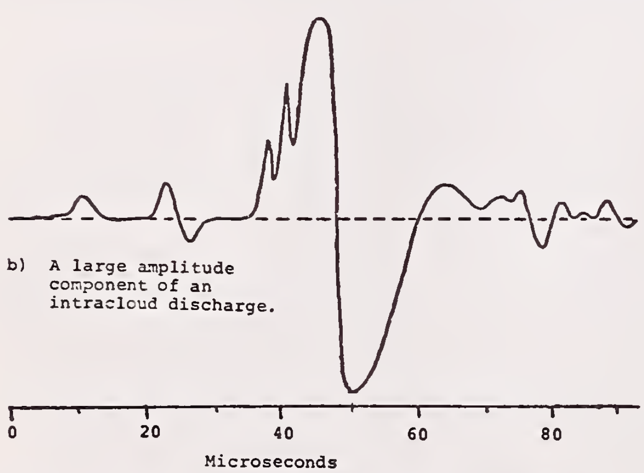
the magnetic fields to have rise times, widths, and multiple peak structures characteristic of return strokes. Intracloud discharges and background noise pulses are rejected if they do not have the proper shape. Accurate bearing angles are obtained by sampling the magnetic field just after the initial radiation field peak (Krider *et al.* 1976; Herrman *et al.* 1976). At the time of the peak magnetic field, the return stroke current is still close to the ground where the channel is nearly vertical and there are no large branches which produce magnetic polarization errors.

Figure 1a shows the shape of the magnetic field produced by a typical first return stroke in a lightning discharge to ground.



a) The first return stroke in a discharge to ground.



b) A large amplitude component of an intracloud discharge.

Fig. 1: Typical Lightning Magnetic Field Waveforms.

The large abrupt transition marked R is due to the onset of the return-stroke current, and the small L pulses preceding this are due to the stepped leader (Krider and Radda 1975). After the first large peak, P_1, there are several subsidiary peaks, P_2, P_3, etc., which are probably due to branch currents (Krider and Weidman 1976). The magnetic waveforms produced by subsequent return strokes in a flash are similar to figure 1a, except that the large subsidiary peaks are usually absent. Extensive studies of lightning in Florida and Arizona (Tiller *et al.* 1976) indicate that 99% or more of the return strokes which produce waveforms like that in figure 1 also transfer negative charge to ground, and thus the polarity of the magnetic field is well-defined.

Figure 1b shows a sketch of the field shape which might be produced by a large-amplitude intracloud discharge. Intracloud discharges occur about twice as often as ground discharges, and very often discharges to ground also have extensive intracloud components. Waveforms such as that in figure 1b may occur individually or in a series of rapid pulses and must be rejected by any system designed to detect only ground discharges. It should be noted that the overall rise time of the pulse in figure 1b is slower than that in figure 1a and that the pulse width is narrower.

APPARATUS

The lightning direction-finding system is shown schematically in figure 2 and consists of a wideband antenna, a pair of 7 m^2-turn vertical loops oriented north-south and east-west (see fig. 3); high- and low-gain signal processing electronics for a wide range of sensitivity; an x-y plotter to record lightning azimuth vectors; and a microprocessor to digitize the data and type the results on a teletype. The antenna system is very similar to that described by Krider and Noggle (1975). The electronics are functionally quite similar to those described by Krider *et al.* (1976), except for improvements in the pulse-shape selection circuits. As we shall see, magnetic fields are accepted if they have rise times, widths, and multiple peaks similar to those in figure 1a and are rejected if they have shapes similar to figure 1b.

In the processing electronics, the output of each antenna loop is amplified and goes to a track-and-hold circuit. The two outputs are also full-wave rectified and summed to provide a direction-independent signal for use in pulse-shape selection. The summed signal is differentiated to determine the time of the first large peak in the waveform, and if this peak occurs within the proper time interval, the NS and EW voltages are held in the track-and-hold circuits. If the pulse-shape circuits verify that the remaining signal satisfies the shape criteria in all other respects, an output is generated

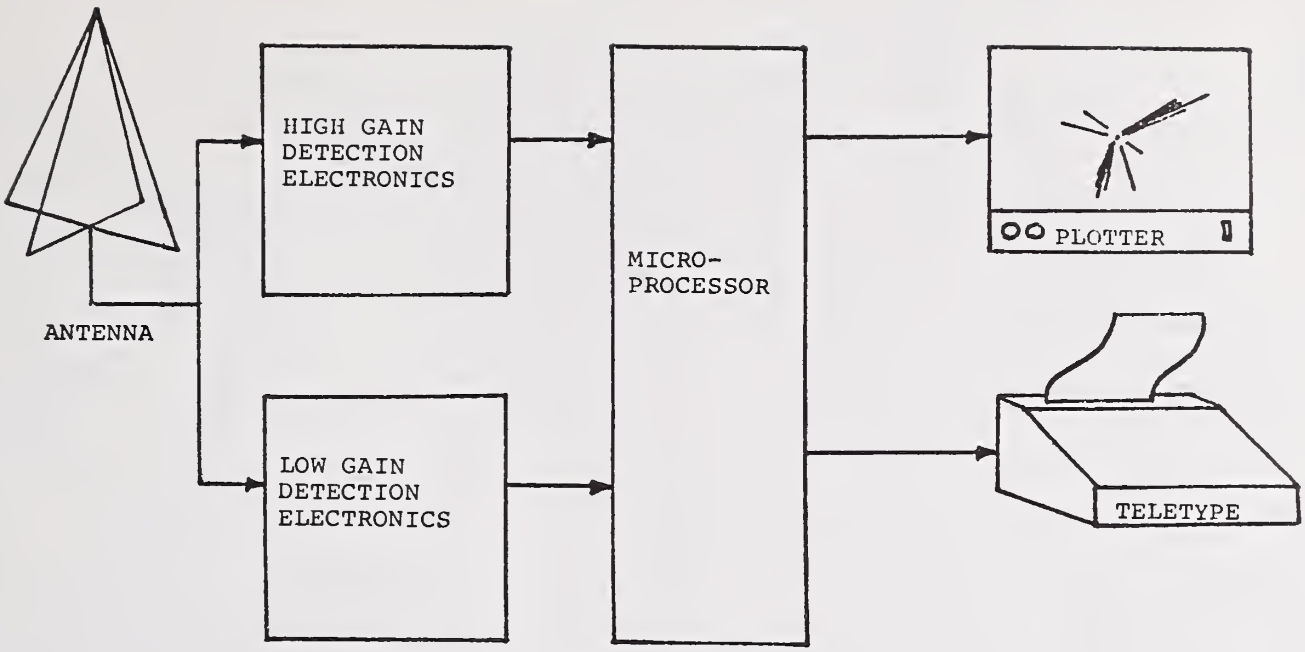


Fig. 2: Block Diagram of the Lightning Direction-Finding System.

Fig. 3--Photograph of the direction-finder antenna at Fairbanks, Alaska.

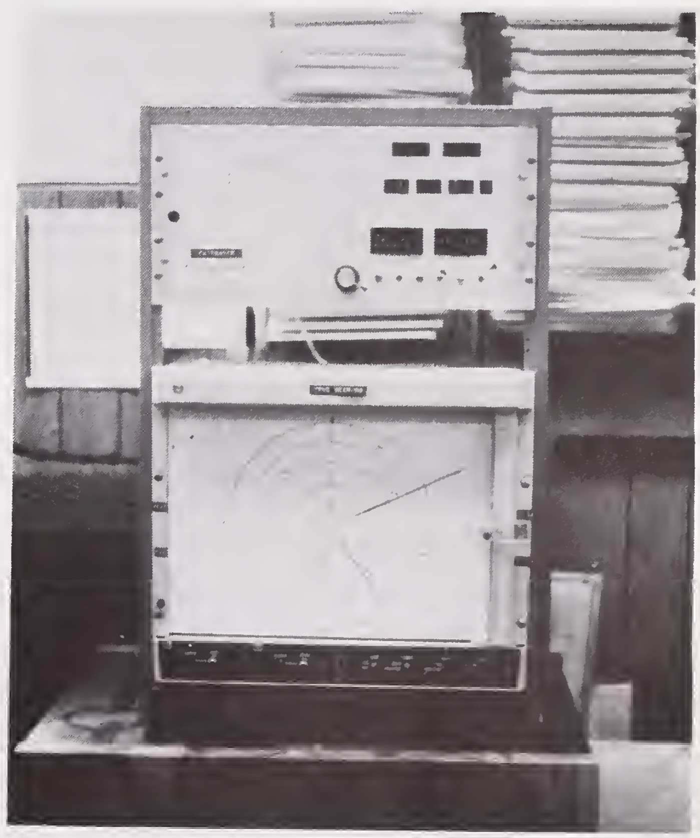


Fig. 4--Photograph of the system electronics and the x-y plotter in Fairbanks, Alaska.

which plots the direction of the incident magnetic field on an x-y plotter and which initiates the microprocessor program. Magnetic signals are accepted if they have a zero-to-peak rise time between 2 and 12 microseconds and if they do not reverse polarity within 20 microseconds after the peak. Additionally, any signal is rejected if it has a subsidiary peak larger than the first within 20 microseconds of the first peak.

The x-y plotter is used to record the angle to each flash according to the NS and EW magnetic signal components. A photograph of the processing electronics and an x-y plotter is shown in figure 4. For each flash, a line segment or vector is drawn in the direction of the discharge from a center which represents the station location. When the system is run without the microprocessor, the vector length is proportional to the peak magnetic field of the first stroke in the flash. When under control of the microprocessor, the length of the vector can represent either an average signal strength or a crude estimate of the range based on this average. In order to extend the dynamic range of the x-y plotter, high- and low-gain results are plotted separately, and the inside end of the vector segment is kept a constant fraction of the total length. If a number of discharges are averaged on the same graph, the resulting pattern of vectors points in the direction of the active storm cells. An example of several vector patterns is given in figure 5. During tests in Alaska, the well-defined groups of vectors corresponding to cells were sometimes accompanied by a few smaller, generally backward vectors due to intracloud discharges. In most cases, these backward vectors were easy to identify and ignore; but an electric field sense antenna and improved pulse-shape selection circuits have subsequently eliminated this problem.

The microprocessor digitizes the signals for each return stroke in a flash; calculates the azimuth angle for each stroke; tests the stroke angles for mutual consistency; computes an average angle and the average signal strength for all good strokes; tests whether the computed angle is within a preset interval desired for output; writes the average angle and signal strength vector on the x-y plotter; and outputs the time, azimuth, and the number of strokes to a teletype. In active lightning situations, the microprocessor can store up to 8 flashes in a buffer memory while new data are being acquired and then output all the data as time permits.

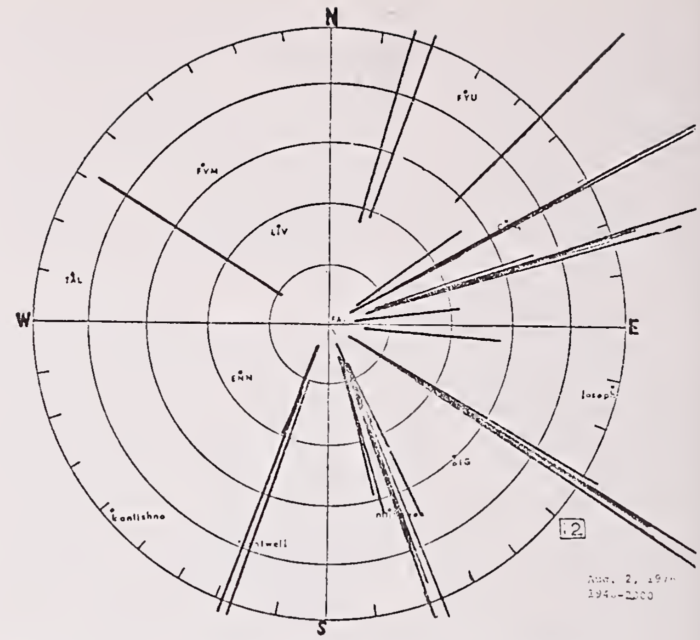


Fig. 5--An example of lightning azimuth vectors obtained at Fairbanks, Alaska, on Aug. 2, 1976. Note the well-defined cells at about 61, 73, 122, 158, and 200 degrees.

SYSTEM PERFORMANCE

The effective range of the above direction-finding system is about 200 nm in interior Alaska and about 300 nm in Florida and Arizona. Large lightning signals can be detected at much greater distances, but beyond the effective range many signals will be missed because they are below the system threshold.

Given the natural variability of lightning, any selection system will necessarily miss some good waveforms, due to fluctuations in shape, and accept some spurious signals. Tests were run on several lightning storms to determine: (a) the efficiency at which return-stroke signals were accepted, (b) the percentage of system triggers which were not good return strokes, and (c) the efficiency at which signals which were large enough to trigger the system, but were not due to return strokes, were rejected. The results of these tests are shown in Table 1. As can be seen in Table 1, the system accepts 70 to 90% of all return stroke signals, and now rejects 97% or more of the improper waveforms. Tucson storms A, B, and C were obtained prior to the addition of an electric field sense antenna and improved pulse-shape circuits. Tucson storms D, E, and F each represent successive circuit improvements.

With the microprocessor, single-stroke

Table 1.--Detector Performance

Storm	(a) Percentage of good return-stroke waveforms which were detected	(b) Percentage of system triggers which were due to improper waveforms	(c) Percentage of improper waveforms which were ignored	Storm Distance (nm)
Fairbanks	68	22	--	125
Tucson (A)	81	10	84	≥150
Tucson (B)	86	8	86	≥100
Tucson (C)	86	5	--	200-300
Tucson (D)1/	71	3	--	~300
Tucson (E)1,2/	88	2	97	100-300
Tucson (F)1,2/	84	1	98	100-300

1/ Additional noise rejection circuitry added.

2/ Composite average of several storms.

flashes can be eliminated by requiring the lightning flash to have more than one return stroke at the same azimuth. This requirement reduces the overall detection efficiency of ground discharges to about 40% (in Arizona), but restricts the output during very active storms to only those discharges with the highest ignition probability.

The angular resolution of the direction-finding system has been measured to be 1-2 degrees or less on a number of discharges near Tucson, Arizona (Krider *et al.* 1976). When the lightning strikes over or behind mountainous terrain, the resolution usually decreases to about 2-4 degrees. In Alaska, a number of flashes from the same distant cell would sometimes be plotted at exactly the same azimuth, and this could only occur if the system resolution is a fraction of a degree, in favorable cases.

The large variability in lightning signal amplitudes prohibits the determination of an accurate range based on the signal strength at just one station. Sometimes, however, an approximate distance can be inferred from the average length of a number of vectors in an isolated cell. Of course, if two or more direction-finding systems are operated simultaneously, accurate lightning locations can be determined by triangulation. Also, when multiple stations are used in coincidence, any spurious vectors due to noise or intracloud discharges will be rejected.

ALASKA TESTS

During the summer of 1976, six lightning direction-finding systems were operated in interior Alaska by the Bureau of Land Management in an effort to improve the detection of lightning-caused fires. Each system operated without the microprocessor and had a useable range of about 200 nm. Six stations, McGrath, Fairbanks, Tanacross, Ft. Yukon, Bettles, and Galena, covered a total area of about 250,000 nm^2 with a multiple-station overlap in coverage over about 130,000 nm^2. Reliable communications were not available between the sites, so each station was operated independently. Weather radar contours were available on hourly intervals at most locations. The lightning vectors were used to pinpoint those radar echoes which were actively producing lightning, and also to indicate which echoes were not active. The angular resolution of the detectors was usually more than sufficient to resolve individual cells of electrical activity within large cloud systems.

The locations of all 1976 lightning fire starts in interior Alaska were accurately correlated with the directions of lightning vectors recorded at one or more sites. BLM fire management and fire weather personnel

found the detector a valuable indicator of the presence and direction of lightning. On several occasions, cloud-to-ground lightning was detected from clouds with radar tops of less than 20,000 ft, where the ambient air temperature was only about -20°C. These cases are of particular interest to both the fire weather and the research communities.

All Alaska tests indicate that the direction-finding system is quite suitable for lightning fire detection and that it can be operated by non-technical personnel. In future years, communications will be added to the Alaska network and triangulation techniques will be employed to pinpoint the locations of all discharges which are detected at more than one station.

Acknowledgments.--It is a great pleasure to acknowledge the generous assistance which was provided by a host of BLM and other personnel during the Alaska tests. We are particularly grateful to R. M. Clithero and J. P. Kastelic for their encouragement and helpful suggestions throughout the program. The microprocessor subsystem was developed with the assistance of Mr. David Scheer of Analog Precision, Inc., Tucson. This work was supported in part by BLM Contract YA-512-CT6-81 MOD1.

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Session III
Fire Danger, Fire Weather and Fire Ecology

Chairman: James H. Richardson, Chief

Division of Fire and Protection Management

United States Department of the Interior

Bureau of Land Management

Washington, D. C.

Meteorological Needs of Fire Danger and Fire Behavior[1]

Craig C. Chandler[2]

Abstract.--More than half the weather-related incidents causing loss of life or property during large wildfires are the result of mesoscale phenomena. Neither the National Weather Service nor the forest fire services are emphasizing mesoscale phenomena in their research or training activities.

Unfortunately, the overwhelming meteorological need if we are to obtain significant improvement in fire danger rating accuracy and fire behavior prediction reliability is much easier to define than it is to achieve. We need accurate, timely forecasts of mesoscale phenomena. Over the past two decades we have seen marked improvement in the general fire weather forecasts as a result of both improvements in the tools and techniques for synoptic analysis by the weather service, and improved communications, forecast packaging, and mutual understanding of requirements by both the fire services and the weather service. These synoptic forecast improvements have paid off handsomely in better, more cost-effective preparedness planning by all major fire agencies. However, they have been of very little help to the fire boss or fire behavior officer in determining expected changes in fire danger and fire behavior on individual campaign fires.

Similarly, over the past two decades, the fire services have achieved a marked improvement in meteorological understanding by training all fire-going personnel in the rudiments of topometeorology. However, this training too has had a less than expected effect in decreasing the number of unanticipated meteorologically related incidents leading to severely adverse fire behavior in campaign fire situations.

Before going further, I need to define synoptic, meso-, and toposcales, since they are used in this paper in a slightly different sense than that of either Geiger or Schroeder. By synoptic scale phenomena, I mean those weather changes that can be predicted by analysis of data drawn from observations taken at the basic synoptic network stations. By toposcale phenomena, I mean those weather changes that can be predicted from analysis of observations taken at a single location together with a knowledge of the surrounding vegetation and topography plus synoptic aids. Mesoscale phenomena, then, are those weather changes which result from causes too localized to be identifiable from the basic network observations, yet too widely separated to be reasonably deduced from observations at a single local station. The timing and strength of marine air penetration into coastal valleys is perhaps a classic example.

Why haven't our improvements in fire weather forecasting and fireman's fire weather training resulted in comparable decreases in large fire incidents? In probing for a reason I examined 32 fire case histories that have been used in national fire behavior training courses since 1957. In only four to six of them were synoptic scale changes a significant feature in altering the fire behavior after the fires had escaped initial attack (I say four to six fires since the Sundance and Okanogan fires were somewhat anomalous). In only one-third to one-half of the fires were the specific incidents selected for study reasonably predictable from single station observations. This figure is fairly loose since most of the examples were derived from single station data by recapitulating backwards from effect to cause. Nevertheless, the results agree well with those of the fire incidents that I have personally investigated--somewhat more than half of the loss of life and loss of acreage in weather related large fire incidents results from mesoscale phenomena. Let's look at two

[1]/Paper presented at the Fourth National Conference on Fire and Forest Meteorology. St. Louis, Missouri, Nov. 16-18, 1976.

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specific cases to illustrate this point.

The Rattlesnake Fire was a small brush fire that started on the Mendocino National Forest in California on the afternoon of July 9, 1953. It was controlled that evening after covering less than 1,500 acres, but in the interim 15 men had been burned to death.

The Rattlesnake Fire was situated in the western foothills of the Sacramento Valley in moderately steep topography at an elevation of 2,000 feet. The Valley floor, 5 miles to the east is at 600 feet, the North Coast Range crest, 18 miles to the west varies in elevation from 6,000 to 7,500 feet. West of the crest lies the Eel River drainage running south to north, then a lower range of mountains, then, 65 miles from the fire, the Pacific Ocean.

The fire originated on the south side of a road that was built along the south side of Powderhouse Creek. To the south, the slope rises 600 feet in slightly less than half a mile to Rattlesnake Ridge. To the north the slope rises 350 feet to a saddle 1,000 feet from the creek and then drops off 1,100 feet to the bottom of Grindstone Creek a mile further north. Powderhouse Creek itself has its headwaters at an elevation of 2,100 feet, just a few hundred yards west of the fire. But Grindstone Creek runs 23 miles to the northwest and drains a sizeable chunk of North Coast Range up to 7,500 feet elevation. Immediately opposite the Powderhouse saddle, Grindstone Creek makes a sharp bend to the east where it empties into the Valley.

During the afternoon the fire moved upslope and control efforts were aimed at stopping the fire from slopping over Rattlesnake Ridge into the next drainage to the south. Plans were to construct a line along Rattlesnake Ridge, anchor it to the road at both ends and fire out from the top down. Burning out operations were begun at about 5:30 p.m. At about 8 p.m. the firing crew was turning the northeast (upper) corner where the fireline tied to the road when local turbulence and fire whirls developed which started several spot fires below the road. Firing out operations were stopped and all but one spot fire were extinguished with tankers. A 19-man crew was assigned to the spot fire that was beyond control by tankers. By 9:30 the spot fire was contained and firing out operations resumed--this time from both ends of the road to make up for lost time. At 9:45 an Assistant Ranger and four men carried lunches to the crew on the spot fire. The line around the spot fire was complete and the Assistant Ranger decided to have the crew eat there before returning to work on the main fire. At 10 p.m. the wind shifted abruptly from upslope to westerly (cross-slope). This caused the main fire which had been slowly backing down towards the road from Rattlesnake Ridge to build up and move rapidly to meet the burning out fire strung along the road. As the two fires met several more spot fires were started below the road, at least one of them across Powderhouse Creek on the south facing slope leading up to Grindstone saddle. This spot, which was out of reach of tankers, quickly burned upslope to the saddle where it was met by a strong northwest wind and took off very rapidly as a wall of flame moving southeast down the Powderhouse drainage. It was now approximately 10:20 p.m.

When the blowup occurred, the 25 men on the spot fire were strung out eating lunches. The nine men highest up the slope elected to go uphill and try to outflank the fire. They barely made it. The 15 men lower down decided to go downhill and downcanyon and try to outrun the fire. The first man was overcome when he had gotten 600 feet from the spot fire, the last man made it 1,500 feet. All 15 died. The fire was controlled before morning at 1,400 acres.

The post-fire investigation showed that the basic cause of this tragedy--the sudden surge of wind through Grindstone saddle and down Powderhouse Creek--is a normal summertime occurrence in that location. It occurs at the end of every hot, clear day in the upper Sacramento Valley when the valley winds give out and the cold air from the mountains slides down Grindstone Creek and, coming to a right angle turn, ride up the slope, through the saddle and down the other side. The timing of this surge is regular as clockwork: between 9:15 and 10:45 p.m. Its duration is short: 30 minutes to an hour. But its occurrence is not one that would normally be predicted, either by a National Weather Service meteorologist with a standard training and background, nor by a Federal or State fire boss with a standard training and background. The cause of the Rattlesnake tragedy lay one drainage away from the fire scene--too far away for the fire boss, and encompassed an area of less than 100 square miles--too small for the synoptician.

A second example is similar yet opposite.

The Elsinore Front on the Cleveland National Forest in southern California is a steep, brush covered, east facing scarp that, in less than a mile, rises from Lake Elsinore at 1,300 feet to El Cariso Pass at 3,200 feet. West of the pass the land slopes more gently to the Pacific some 20 miles away. A two lane paved State highway winds across the face of the front to connect the interior valley towns to San Juan Capistrano on the coast. At 6 p.m. on August 8, 1959, a car failed to negotiate a curve, went

over the embankment, rolled 600 feet down the slope and burned. The fire was reported almost immediately and California Division of Forestry crews responded from the town of Elsinore and U.S. Forest Service crews from El Cariso Guard Station just west of the pass. The fire was spreading rapidly downhill pushed by a steady downslope wind. The CDF crews were assigned the lower edge of the fire with instructions to keep the fire from crossing the highway and to protect ranch properties and outbuildings that dotted the edge of the lake. The Forest Service crew was to control the upper edge of the fire, keep it from crossing the highway and construct a line down the fire's north flank to complete containment.

After two attempts to construct a flank line had to be abandoned, the Forest Service Ranger decided to fire out a half mile of highway and tie in to a 150 acre burn that had occurred 3 weeks before. At about 7:30 p.m. 25 men were spaced out between the fire edge and the old burn and set to chopping brush along the edge of the highway to facilitate the firing out operation. The actual firing was to proceed from the fire edge up the road to the old burn. By 8 p.m. the four-man firing crew supported by three tanker-pump units had progressed about 200 yards up the road. Then, suddenly, the wind stopped and, according to survivors, "for about half a minute the fire seemed to be burning in a vacuum." Then all hell broke loose. Within a few seconds sheets of flame, sand, gravel, and rocks the size of baseballs whipped across the 25 to 35 foot wide highway along a 100 to 200 yard stretch of road at the head of the backfire. At the same time the main fire made a series of runs up the small drainages along the entire stretch of road leading to the old burn.

The tanker operators immediately put their equipment into reverse gear and backed downhill to where their backfire had already burned out a safe distance. All 29 men ran down the road after the tankers. The firing crew and the first six men reached safety unharmed. The 12 men in the middle received various degrees of burns on their hands and faces. The seven men furthest uphill were critically burned and five of them died of their injuries. The paint on the downslope side of the middle tanker had melted and was imbedded with sand and small pieces of gravel. The paint on the uphill tanker had been burned and sandblasted completely away.

What caused this tragedy? Why should apparently well established downslope winds reverse themselves in late evening? What could cause a relatively small fire to sweep flame across a 25 to 35 foot wide highway nearly simultaneously along a one-half mile front? As in the Rattlesnake disaster, the keys lay some distance from the fire itself.

In 1959 "Lake" Elsinore contained not a drop of water, but was a barren, sun-baked mud flat 2 miles wide and nearly 5 miles long situated 2 miles east of El Cariso Pass and slightly over a mile east of the base of the mountains. In the 100 degree plus days of summer, convection from the dry lakebed is strong enough that it is a favorite haunt of sailplane pilots. To the east El Cariso Pass is the lowest spot where cool air from the Pacific can pour in to the interior valleys. In the morning when the east facing slopes of the Elsinore front warm more rapidly than the lakebed upslope winds are formed. At noon, when upward convection from the lakebed is fully developed, the heated slopes still provide enough buoyancy to keep the eastward flowing cool air from reaching the surface. But by early afternoon when the sun hits obliquely on the 40 percent slopes, downslope winds start forming and reach their peak velocities prior to sundown. When the lakebed is shadowed, an hour or two after the slopes, convection stops apparently rather abruptly. As the air in the basin stabilizes, inflow through the pass is reduced and the downslope winds abate, or even reverse themselves for an hour or two if the slopes are still warm enough. Later in the night radiational cooling produces "normal" downslope winds along the front.

At the time of the breakdown in downslope winds, the Decker Fire was actively burning in flashy fuels on an 80 acre flat at the base of the mountains and bounded on two sides by spur ridges. When the winds stopped, the sudden release of heat set up an eddy over the flat which moved upslope and developed into one or more large and extremely intense fire whirls. As one whirl moved upslope to the scene of the tragedy it triggered runs up all the spur drainages in its path. Fortunately, the whirl itself crossed the road at a point where the burning out operation had already removed appreciable fuel. Otherwise the loss of life in this incident would undoubtedly have been greater.

Here again we have a situation that is a normal daily climatic phenomenon for the area involved, but one which would not be readily predicted by either the synoptician nor the topometeorologist.

So what do we do about it? I don't claim to have all the answers, but one thing I'm sure of--we need to have more top quality people thinking about it. Two decades ago, when Forest Service Research was considerably smaller and poorer than it is now, Countryman and Schroeder initiated a series of "Fireclimate

Surveys" that were intended to provide an initial series of case history studies from which generalizations about the dynamics of mesoscale phenomena could be made. Over the years this effort petered out as their time and resources were redirected towards other, more seemingly urgent lines of research. Two decades ago, when the U.S. Weather Bureau was considerably smaller and poorer than today's National Weather Service, fire weather forecasters used to spend part of their winters analyzing and documenting their past seasons fires with the aim of providing better localized service. I haven't seen any such analyses lately. Again, I suppose, because of "higher priorities" elsewhere. I suggest we reexamine our priorities. There is a large gap in our training, our forecasting aids, our observation networks, and even in our basic understanding of weather processes on the mesoscale that will have to be filled before we can expect to see significant improvements in our fire weather forecasts on large fires.

Two actions could be taken now, without any new grandiose programs, or even any new budget increases. We, both the fire weather forecasters and the fire behavior officers, could and should return to the habit of carefully recapitulating and documenting the meteorological history of every fire we attend. Time and time again case histories have proven their value as training aids and as sources of research data. To neglect this documentation because of other work pressures after getting back from a fire is to waste at least half of the value of having been on the fire in the first place.

Second, we can and should insist on more and better weather observations on both prescribed burns and large wildfires. I have always felt it anomalous that the Weather Service spends at least five times as much to equip its mobile units with telefax equipment as it does to provide them with portable recording weather stations. It is, of course, easier to draw curves from a single data point, but the results don't necessarily inspire much confidence. In some instances the fire agencies have tried to make up for this deficiency by utilizing their own weather observers (the Weather Security Watch system established by John Dell in Forest Service Region 6 is a good example), but this is a poor substitute for four to six recording stations strategically placed by the fire weather forecaster.

So in conclusion, as in the beginning, what we need are accurate, timely mesoscale forecasts. Whether or not we ever get them is largely up to the people in this room.

Meteorological Needs for Fire Management Planning[1]

R. L. Bjornsen2/

There are five principle categories of fire management planning which have meteorological needs; many of them common. Meteorological data is essential to execution of fire plans. The data, historical and forecasted, is an integral part of each fire plan. There is shared responsibility between user agencies and National Weather Service to negotiate a common plan which will translate needs into reality.

Planning is not unique to fire management. Rather, it is a common denominator in the success equation for all endeavor. But fire managers, like others who seek goals and objectives, must develop plans to achieve them. In his case the fire planner has meteorological needs which must be satisfied. Before looking at these let us see the type of plans the fire manager deals with.

Traditionally fire management planning falls into the following categories:

- Presuppression
- Preparedness
- Prevention
- Suppression
- Prescribed Burning
- Natural Fires

Later we will see how each of these categories has meteorological needs. But first let us clarify that this paper will treat meteorological needs for fire management planning in a broad context, rather than the specifics of data required and hardware configuration.

Earlier in this conference Tikkala 3/ and Wilson 4/ set the stage for protection agency needs in the operational arena. One thing made abundantly clear by their papers is that meteorological data is essential to execution of fire plans. We cannot deny this truism because the effects of weather, short and long term, upon the wildland resources we administer are profound. The fire planner must incorporate meteorological data into his plans if they are to be successful in operational execution.

It is meteorological data, historical and forecasted, which then becomes an integral part of each fire plan. Often a common meteorological data base will serve more than one type of plan. This fact needs to be exploited by the planner. Nearly every plan has a unique requirement for meteorological data. Let us examine what these needs are for the principal categories of plans. Since there is a commonality between various plans, Table I would seem to serve well to identify commonality yet focus on unique needs where they exist.

The tabulation is not all inclusive, but only intended as a guide to place meteorological needs for fire management planning in perspective and emphasize the important role which meteorological data plays in the fire planning process.

1/Paper presented at Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.
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3/Department of Agriculture Needs for Specialized Weather Forecasting.
4/Land Managers Needs for Weather Service and Advice.

METEOROLOGICAL NEEDS FOR FIRE MANAGEMENT PLANNING TABLE I

PLAN	NATIONAL DATA BANK FIRE WEATHER STATISTICS	EXTENDED FORECASTS 24-72 HOURS	LONG RANGE OUTLOOKS	WILDLAND DROUGHT FORECASTS	PORTABLE RECORDING WEATHER STATIONS
Presuppression	X				X
Preparedness	X	X	X	X	X
Prevention	X		X	X	
Suppression		X	X		X
Prescribed Burning		X	X	X	X
Natural Fires	X			X	X

With one exception I will not burden the reader with descriptions of the various categories of plans, he will have to accept they serve mostly different goals and objectives. The exception is natural fire plans; goals, objectives, and execution of which can vary greatly between agencies.

Suffice it to say for purposes of this paper, that natural fire plans are those which accommodate fires that are usually monitored (for whatever objective), as they burn rather than fires where aggressive suppression action is taken.

How do we translate needs into reality? This is a shared responsibility between user agencies on the one hand and National Weather Service (NWS) on the other. Note I have named NWS specifically here. This is because user agencies universally identify NWS as the principal entity for supplying meteorological input to meet both planning and operational needs, particularly in the fire area.

Back to reality. The user agencies have responsibility for identifying their needs, establishing performance expectations and determining program target dates. Whereas NWS has responsibility for determining how meteorological needs will be met, when they can be met and funds required to support the programs, then becomes a joint responsibility to negotiate a common plan which will translate needs into reality.

Returning to the occasionally abstract world of the fire management planner, we see that meteorological data is essential to execution of fire plans and therefore essential to the planning process. Somewhere, somehow we must translate these needs from the drawing board into reality. There is no panacea for achieving this, we can only be encouraged by the anonymous simile which says: everything that is done in the world is done by hope.

Meteorological Resources for Land Management[1]

Robert C. Lamb[2]/

Abstract, —Several types of meteorological resources are available to land managers. Among those are data, service, research, and the land managers themselves. We are not utilizing existing meteorological data as effectively as is needed and we need better sampling over time (both throughout the year and diurnally in the Forest and rangeland environment).

The special service meteorological resource for land management does not exist. It should and we should take the steps now.

The research resource must insure that its products past and present are carried through to operational usefulness.

The users of meteorological resources are a resource in themselves, and to be effective, must identify and fulfil the responsibilities necessary to effective use of this resource.

The comments here are designed to assist in defining the meteorological resources available and potentially available to land managers. Positive progress requires commitment by users as well as providers of meteorological resources.

I INTRODUCTION

Dr. Furman has just provided an example of a specific meteorological resource for land managers. I want to take this opportunity to broaden our scope in examining meteorological resources. To address this area, I have stratified meteorological resources into four categories:

1. Meteorological Data Resources
2. Meteorological Service Resources
3. Meteorological Research Resources
4. Meteorological User Resources

I established these categories because I believe it is important that we look briefly at the strengths and weaknesses of each. Hopefully, the comments to follow will help take us a step toward better understanding and utilization of meteorological resources for land management.

1/Paper presented at Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.

2/Meteorologist, U.S. Forest Service.

II METEOROLOGICAL DATA RESOURCES

In the States of Oregon and Washington, substantial meteorological data are collected. These states are used because of my familiarity with them, but they are typical of much of the rest of the country. Weather data is available from:

1. About 300 fire weather stations taken on a daily basis during the fire season. This data spans from a few years to several years and is available in the National Fire Weather Data Library at Ft. Collins, CO. Brink, & Furman.
2. 350-400 climatic stations that measure maximum and minimum temperature and precipitation daily.
3. Three upper air monitoring stations (Quillayute, Wash., UIL, Salem, OR, SLE, & Medford, OR, MFR.)
4. An interagency Columbia River basin hydromet network encompassing numerous stream gagging, and precipitation and snow measurements.
5. One weather surveillance radar system with additional back up from ARTC radars.
6. About 35 hourly reporting stations taking complete observations excluding solar radiation and soil temperature in both States.
7. Satellite pictures from the GOES on a half hourly basis with selectable resolution from 1/2 mile visual during the day to 1, 2, or 4 mile resolution IR and visual. Incidentally, these are not available to special service

program offices.

Data mentioned in two through seven above is stored at the National Weather Records Center in Asheville, NC. This list is not all inclusive, but nevertheless represents the collection and storage of enormous quantities of meteorological data. In spite of this substantial resource, we have very limited data and observations from the actual land management environment exclusive of the daily observations from fire weather stations during the fire season.

Some items are worth emphasizing at this point. First, we are not effectively utilizing the meteorological data that presently exists to assist in land management activities. e.g., climatological summaries, including the use of conditional climatologies designed to specifically address land management needs. Secondly, there still exists a need for better sampling of the Forest and rangeland environment both diurnally and throughout the year. Finally and of substantial importance is the need for quality equipment and observations at land manager maintained sites.

III METEOROLOGICAL SERVICE RESOURCES

Let us now examine briefly the meteorological service resources available in the States of Oregon and Washington, there are:
1. Fourteen manned weather service offices in the two States, eight of which are staffed with professional meteorologists and six with meteorological technicians. Six of these offices have specialized Fire Weather programs.
2. Two weather service forecast offices providing forecast guidance to the respective States.
3. One river forecast center manned by professional meteorologists and hydrologists.
4. One weather service office for Agriculture manned by a professional meteorologist.

Again the service resources here are not all encompassing, but do indicate substantial service resources that receive, develop and disseminate information that may be useful in land management activities.

Let us reflect momentarily on the service resources, specifically the specialized service programs, e.g., Fire Weather and Agricultural weather. The special service programs and people in these programs are important because they, by design address specific needs. They differ in important ways from people in other meteorological service programs in that they:
1. Have an opportunity to conduct training for the users in basic weather and forecast interpretation. This is an extremely important function because it relates to the area of greatest potential improvement in forecast information that exists at this time, i. e., communications. For example, have you ever asked yourself how much of the information contained in the narrative portion of the forecast goes unused because it is not understood? Have you thought about some means of delivering live weather briefings to land managers?
2. Have an opportunity to develop a better understanding of user activities and needs and thereby select, develop and provide weather and forecast information that is most appropriate to the users needs.
3. Can conduct localized forecast improvement, climatological studies etc., that will enhance the forecast service and use of other meteorological information.

You should remember that there are special meteorological service programs in the Fire Weather, Agriculture, Marine, Aviation, etc., but, there is no specialized service program addressed to the sum total of Forest and rangeland management. Can we derive positive benefits through considering the pooling of Agriculture and Fire Weather and expanding these into a viable land management special service program?

IV METEOROLOGICAL RESEARCH RESOURCES

The data and service resources mentioned above related to the States of Oregon and Washington but are generally typical of other areas. The meteorological research resources are more limited and we will look briefly at these on a National level. They are:
1. Research at the National level in Washington by the National Weather Service principally oriented toward model improvement, development and use of model output statistics.
2. Meteorological research conducted by the Forest Service at the three fire laboratories (Macon, Georgia; Riverside, CA; and Missoula, MT,

the Mountain Meteorology project at Ft. Collins, CO. and peripheral work at several hydrologic laboratories.
3. Meteorological research conducted at several universities.
4.Meteorological research conducted, completed, in journals or papers residing on shelves, but otherwise unused.

Again this is not all encompassing. However, it is well recognized that meteorological research specifically oriented to land management activities is very limited indeed. Even the Forest Service meteorological research has been principally oriented towards fire. The Forest Service appears ready, as evidenced by the current scope of atmospheric science research, to address the broader concept of meteorology and land management.

Item 4, completed research is the resource that is most readily available, but application in present forms may prove difficult without further refinement and framing into an operational mode. By the same token, we need to have ongoing research carried on through to the point that it is also operational. This is of particular significance when you consider that the land managers of whom we speak are not either academically or operationally trained in the use of meteorological resources.

V USERS OF METEOROLOGICAL RESOURCES

It may seem strange to you that I would mention users when I talk of meteorological resources. However, I have become increasingly convinced that this is a resource that ties the total picture of meteorological resources together. The user must understand that he has a responsibility to know how to effectively use resources available to him as well as have the ability to maintain and collect additional resources (Weather stations and observations).

Earlier, it was stated that training is an essential part of an effective specialized service program. It is equally important that users of meteorological resources be ready, willing and able to receive that training.

The philosophy to be imparted here is that the people who provide meteorological resources are not the only people who have responsibilities related to the use of meteorogical resources. For example, how many position descriptions in your agencies or companies make it clear that the individual has a responsibility to know how to effectively utilize weather information? The simple knowledge that a responsibility exists, allows for accountability and provides a substantially better stimulus to receive training and make effective use of training.

Who is responsible for maintaining quality standard weather stations and observations? Will an annual or less frequent visit to a weather station suffice? The States of California, Oregon, and Washington and Region Six of the USFS have meteorologists on their staff to assist in the application of meteorological resources. How many other companies, states, Regions and other land management agencies have taken that same step?

VI SUMMARY

In summary, we indeed have substantial meteorological resources. These cover enormous quantities of data, substantial services, research and users or potential users. Relative to application of meteorological resources to land management, we fall far short in several important areas:
1. We are not effectively utilizing existing climatological data.
2. We are in need of better sampling of the land management environment.
3. We are not receiving adequate training and local forecast improvement work from existing special service programs.
4. We do not have a special weather service program that addresses land management needs as such. Present services are bootlegged on other programs.
5. Much of the meteorological research in the past has not been carried far enough to become operationally useful to land mangers.
6. Users or potential users of meteorological information have not accepted or identified their own responsibilities for effective use of meteorological resources.
7. We need to develop new and better ways of communicating current and forecast weather information to land management people.

We can move forward in the effective use of meteorological resources for land management. Progress in that direction requires action on the part of research, operational meteorologists, and the land managers. Furthermore, to be effective, the action should be a combined and sustained effort. I say this because of concerns I have seen expressed regarding the Fire Weather Service. I believe these concerns are a positive indicator of desired improvement in that part of a special service program. I do not see evidence of what I think should be equal concerns in the other areas, e. g., land managers, research, and data resources. Furthermore,

I have not seen concerns for doing the total job relative to land management which is indeed much broader than Fire weather.

Are we ready to address a special weather service program with support from land managers and research whose mission is meteorological and climatological support to land management? Does this concept better fit the needs of land managers and will we achieve more effective benefits from the dollars and effort expended?

I believe the answers to the above questions are affirmative and that we can move a long way forward in the application of meteorological resources for land management. This move ahead requires a definite commitment on the part of users as well as providers of service and research.

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USDA Forest Service
General Technical Report RM-19
Rocky Mountain Forest and Range
Experiment Station, Ft. Collins, CO.
December, 1975

Meteorological Resources for Land Management[1]

R. William Furman[2/]

Abstract.-- A collection of weather observations that may be described as a computerized meteorological data source has been made available to users on the USDA computer in Fort Collins, Colorado. This data library is a source of unique data since most of the observations are from remote forest and mountain locations. Many of the stations have records exceeding 20 years. The data in the library is accessible either in remote batch or interactive mode. An integral part of the library is the support programs which make the library highly user oriented and allow the user to extract selected amounts of data for his use. The purpose of the library is to make meteorological data easily available to land managers and to promote the use of meteorological data in resource planning.

In this era of environmental awareness, managers of public lands must be aware of possible outcomes of any management practices they prescribe. They particularly need site weather data from the managed areas--both real-time information and historical data--for input to fire-planning and water-yield models to name two good examples. Improvement of fire weather forecasts requires historic data for verification efforts. The best long-range forecast a land manager can get comes from an analysis of his climatological data.

Where the analysis of weather data is a part of routine land management practices, the data should be recent, easily obtainable, and in computer-compatible format. Optimally it is desirable to include this year's data into plans for next year. Where forecast verification is concerned, it is desirable to analyze this year's forecasts to make adjustments next year.

The Forest and Mountain Meteorology Project at the Rocky Mountain Forest and Range Experiment Station in Ft. Collins, Colorado, and the National Fire Danger Rating Project in Missoula, Montana have assembled and currently support a Computer Oriented MEteorological Data Library on a government computer. The COMED Library consists of a collection of recent and historical fire-weather observations, recent fire-weather forecasts, and the support programs necessary to use the Library.

At present the COMED Library consists of more than 1.5 million fire-weather observations from nearly every State and from nearly all fire management agencies including USFS, BIA, BLM, and many States. These data were initially collected by fire managers for input to daily fire management decisions. This effort was necessary because the National Weather Service observing stations were not located where they could monitor weather conditions meaningful to fire danger problems in forested areas. Federal agencies concerned with fire protection established their own network of weather observations stations in locations where the fire danger could be more accurately monitored. This fire danger network has grown to more than 800 stations monitoring weather once daily, usually during the early afternoon when fire danger is the highest.

The main source of most of the recent data in the Library is the fire danger rating interactive computer program AFFIRMS. AFFIRMS archives all fire-weather observations it receives, and at certain intervals commits the archived data to magnetic tape, a copy of which is sent to the Forest and Mountain Meteorology Project in Ft. Collins. These data are made available to the users of the Library within a week of their receipt.

1/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, Nov. 16-18, 1976.

2/ Meteorologist, Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Fort Collins, Colorado.

Another source of data is the historic records occasionally received from stations not using AFFIRMS and from old stations. These data are edited for proper format then put on the Library.

The COMED Library was designed to facilitate the archiving and retrieval of the large number of fire-weather observations used in our research effort. Because of a similar need for the same data by fire planners, a copy of the Library was moved to the USDA Fort Collins Computer Center and made available to all users.

The Library system has four main parts:

1) Collective tape
2) Library tapes
3) Forecast tapes
4) Support programs

As data are received from AFFIRMS or any other source, they are edited, sorted, and merged onto the collection tape. These data are available to anyone having a need for current-year data. In January of each year the collection tape is merged onto the Library tapes and a new collection tape is started.

The Library tapes are the repository for all but data received during the current year. The Library tapes are a sequence of tapes on which the fire-weather observations are stored by station number, then by date.

Forecasts received from AFFIRMS are stored on a separate Forecast tape. These forecasts are made available in the same manner as data on the collection tape for the current year; then they are destroyed. No historic forecast data are kept. Retrieval of information stored on the Collection, Library and Forecast tapes is facilitated by a collection of routines called GETDATA available to all users as part of the Library system. These routines make the Library a user-oriented system. The tasks GETDATA will perform are:

1) Obtain file names of all data files, along with data limits on the contents of the file.

2) Obtain a station-year-record inventory of a selected data file.

3) Create a user file of selected station-years of data from any or all of the Library and Collection and Forecast tapes.

4) List data from user data file.

As a modest degree of protection against loss of data, two duplicates of the entire Library, Collection, and Forecast tapes are kept: one at CSU and one at the Rocky Mountain Station.

In summary, we have described a computerized meteorological data source designed to be used by people who are not computer specialists. This includes land and resource managers.

The Library is a source of unique data since most of the observations are from remote forest and mountain locations. Many of the stations have records exceeding 20 years. The data in the Library are easily accessible in either remote bath mode or interactive on the USDA computer in Fort Collins, which is available to most land management agencies. 3/

Relatively recent fire-weather observations and forecasts from AFFIRMS are available as well as historic observations. Even though most of these station records are seasonal, they may be used with year-round records from the National Weather Service climatological stations to estimate conditions at the fire-weather stations year round.

One of the important uses of this data library is to establish climatologies of the fire-weather stations. Many have records of sufficient length to obtain stable estimates of the climate variables. Efforts are underway to help fire and land managers determine what a useful climatology should contain, and help them use it.

3/ Furman, R. William and Glen E. Brink, 1975. The National Fire Weather Data Library: What it is and how to use it. USDA For. Serv. Gen. Tech. Rep. RM-19. 8p. Rocky Mtn. For. and Range Exp. Stn., Fort Collins, CO 80521

The National Fire-Danger Rating System — Latest Developments[1]

John E. Deeming[2/]

Abstract.--Extensive use of the 1972 version of the National Fire-Danger rating System has pointed up deficiencies that the 1978 update is expected to correct. Eighteen fuel models will be provided as well as a completely overhauled fire occurrence module. The system will respond to longer-term drying, and changes have been made that will make the system better reflect seasonal trends in fire danger due to changing sun angle and day length.

INTRODUCTION

Fire-danger rating, like all technologies, is advancing. The current development program, which began in 1968, produced a system based on equations that describe the physical processes of moisture exchange between fuels and the environment. It also considers the effects of wind, slope, fuel moisture, and fuel particle and bed properties on the combustion processes. The system provided indexes relating to rate of spread, available fuel energy, fire containability, and fire incidence (Deeming and others 1972).

The system, as it was released for use in March 1972, represented the state-of-the-art of fire research in the United States. At present, the National Fire-Danger Rating System (NFDRS) is being used by all Federal land management agencies and by fire management organizations in 39 States. Last summer in the Continental U.S. and Alaska, more than 750 fire-weather observations per day were being processed by the AFFIRMS time-share computer program (Helfman and others 1975). An additional 500 observations per day are estimated to have been processed manually or by locally operated computers, as is done in Hawaii.

When the NFDRS was released in 1972, an update was planned for 1978 to correct the deficiencies that were expected to surface with widespread use. The NFDRS Research Work Unit, located at the Northern Forest Fire Laboratory, has nearly completed this task. In this paper, the major problems in the 1972 NFDRS are identified and the planned corrective measures are described.

RESPONSE TO DROUGHT

Because the largest fuel considered in the 1972 NFDRS had only a 100-hour timelag, the indexes fail to reflect the effects of long periods of below-normal precipitation. Previous research had shown that fire behavior is almost totally governed by the condition of fuels less than about 3 inches in diameter, so the initial problem was to discover the avenue by which long-term drying influences fire behavior.

The most logical and intuitively acceptable response to long-term drying was hypothesized

1/ Paper presented at the Society of American Foresters-American Meteorological Society Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, November 16-18, 1976.

2/ Project Leader, National Fire-Danger Rating Research Work Unit, Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 507 25th Street, Ogden, Utah 84401. Located at the Intermountain Station's Northern Forest Fire Laboratory, Missoula, Montana.

to be the moisture content of the live fuels--herbs, forbs, and the twigs and foliage of woody shrub species. In addition, by using Rothermel's spread model (Rothermel 1972), we determined that dead fuels up to 15 cm (6 in) in diameter with a surface area-to-volume ratio of 3.5 cm^2/cm^3 (9 in^2/in^3 should be included. Thus, we felt that the 1,000-hour timelag class could be justified for some of the fuel models.

Predictive equations for the 1,000-hour timelag fuel moisture were derived from existing theory (Fosberg 1970), but for the live fuels equation development was much more difficult. The details of the primitive live fuel moisture model that we developed will be published soon.

Briefly, the model considers three classes of live fuels: the lesser vegetation that will cure; the lesser vegetation that will not cure; and the twigs and foliage of shrubs. The moisture contents are assigned standard values when the spring flush is observed. The daily changes in the living fuel moistures are functions of the change in the 1,000-hour timelag fuel moisture value (the sign and magnitude are considered).

Consideration is also given to the climate at the recording station. Five different sets of responses are provided so that the adaptations of native vegetation to the local climate can be accounted for.

A side benefit from the incorporation of this model in the NFDRS is the elimination of the need for direct sampling of herbaceous vegetation by the users. An examination of data from the transects has shown gross inconsistencies which, because of the sensitivity of the system to this parameter, must have produced significant errors in the NFDRS ratings.

I must emphasize the adjective "primitive" in describing the live fuel moisture model. I want to leave no illusions concerning the finality of the solution. Much work remains before an adequate accounting for the phenology of live fuel species can be made.

SEASONAL VARIATION

The 1972 NFDRS tends to overrate fire danger during the late summer and fall. The Canadians have, for some time, accounted for the seasonal variation of insolation and the resulting effects on the moisture exchange processes, but up to this time we have not.

We attacked the problem from three directions: First, the effect of a varying sun angle on the temperature and relative humidity in the boundary layer are accounted for. These are significant in the calculation of the 1-hour timelag fuel moisture. Second, in the calculation of the moisture contents of the 100-hour and 1,000-hour timelag fuels, instead of a simple average of the 24-hour maximum and minimum equilibrium moisture contents, a weighted average is used to characterize the drying characteristic of the day. As the period of daylight shortens, the nighttime conditions are given increasing weight, thus promoting moisture recovery in the heavy fuels. Third, the fuel moisture analog (half-inch sticks) value is being considered in the calculation of the 1-hour timelag fuel moisture content. Using an analog is by far the simplest approach because all of the seasonal associated influences are automatically accounted for and integrated in the fuel stick response.

Robert Burgan will discuss this aspect of fire-danger rating in a paper later in this conference.

RATING SENSITIVITY

Because of the desirability of utilizing a finite 0-100 scale for the ratings, we made an error in the 1972 NFDRS that has caused many of our users a great deal of concern. We chose such severe conditions to be represented by index values of 100 that fire managers in the relatively moderate fire climates of the country seldom see ratings greater than 8 or 10.

This lack of sensitivity of the ratings to changing burning conditions has caused many to judge the NFDRS inadequate. This is an unfortunate situation because the problem was caused by a poor choice of scaling factors; not by shortcomings in the basic, underlying theory and equations.

The problem has been solved by making the scales open-ended. The spread component is numerically equal to the predicted ideal rate of spread in meters per minute, and the energy release component is numerically equal to available energy in megajoules per square meter. The burning index equals 50 when the predicted ideal flame length is 3.4 meters (11.3 feet). This value was chosen as the basis for normalizing the burning index because there is a significant probability that a fire with this potential will be uncontrollable if it escapes initial attack. This flame length occurs when the fireline intensity reaches 960 watts per meter of fireline (1,000 Btu per second per foot).

These changes will result in a three-to-five fold increase in sensitivity of the burning

index and a doubling of the sensitivity of the spread component.

FIRE OCCURRENCE

In the 1972 NFDRS, the occurrence module was very simplistic. It was based on what turned out to be pretty sound rationale, but we have made some significant changes.

The most apparent change will be the separate ignition, risk, and occurrence indexes for man-caused and lightning-caused fires. This partitioning is justified because the processes are different, and it is only reasonable that man-caused and lightning-caused fires be accounted for separately.

The man-caused fire ignition component differs slightly with the different fuel models. Rate of spread is now a factor along with fine fuel moisture and temperature. The model is a linear model developed from fire danger and fire occurrence data collected in the Northeast. The model remained linear when checked against data from the Southwest. A computer program that analyzes local fire weather and fire report data is being prepared. It will establish the relationship between the index values and probable fire occurrence levels on the individual protection unit.

The lightning occurrence index was developed from data accumulated from Project Skyfire studies in the Northern Rockies. Data on storm size, lightning frequencies, and the prevalence of cloud-to-ground strokes capable of starting fires have been correlated with the five existing lightning activity levels. A sixth lightning activity level has been added to account for the classical "dry" lightning storm situation.

FUEL MODELS

In the 1972 NFDRS, the user is given a choice of nine fuel models. Many users feel that fuels in their areas are not adequately represented, while others have expressed the opinion that such a range of choices is not needed to rate fire danger.

The question of how many fuel models are needed remains unresolved. In the absence of a means to objectively determine an optimum number, we have decided to offer an expanded set of 18 models, leaving the option of utilizing more or fewer models to the user agencies.

Here is a list of the 18 fuel models that we plan to offer. The models carried over from the 1972 NFDRS are indicated by their alphabetic designator.

Grass and grass-like

- Western annual grasses
- Western perennial grasses - - - - A
- Everglades sawgrass
- Tundra

Savannah

- Open timber with grass - - - - - C

Brush

- Mature California chaparral - - - B
- Intermediate chaparral
- High poccossin
- Southern rough (palmetto-gallberry) - - - - - - - - - - D

Timber

- Short-needled conifer--heavy dead - - - - - - - - - - - - - G
- Short-needled conifer--normal dead - - - - - - - - - - - - - H
- Long-needled conifer--normal dead
- Alaskan upland black spruce
- Hardwoods--summer
- Hardwoods--winter - - - - - - - - E

Slash

- Heavy - - - - - - - - - - - - - - I
- Medium
- Light

The models have been improved with the addition of 1,000-hour timelag and live fuels where justifiable. Also, the extinction moisture content and percent of the herbaceous fuels that will cure are characteristic of the fuel model.

I must be candid about these fuel models. Very little data exist on the properties of the fuels found in many of the situations that these models are supposed to represent. The exceptions are the grass, chaparral, slash, and southern rough models. Where data were not available, the models were constructed using whatever knowledge was available. They were then adjusted so that the predictions of flame length and rate of spread made using the fire behavior models fell within acceptable limits.

The lack of reliable observations of fire behavior has been a handicap in evaluating the performance of the fuel models. Subjective evaluations by fire management personnel are being made, but more often than not, the opinions conflict.

Perhaps there is a truth emerging that we should face up to. Fuels vary a great deal from one point to another within a type. Stylized fuel models can be very useful, but we should not allow ourselves to develop unreasonable expectations concerning the accuracy of predictions based on these models. A larger number of fuel models will not result in more precise predictions of fire danger. Instead, the uniqueness of the fuel models will be lost and their usefulness will be lessened. Thus for our purposes, a limited number of fuel models is desirable.

THE FIRE SPREAD MODEL

Rothermel's fire spread model remains the basis for the spread and energy release components and the burning index in the NFDRS. Fire behavior modeling is continually evolving and we are taking advantage, when possible, of each applicable advance. At this time, the principal changes to be incorporated into the 1978 NFDRS are: (1) a new calculation of burnout time; (2) an improved calculation of the extinction moisture content of live fuels; and (3) a more realistic handling of live fuels. The model allows for the loss of the energy necessary to dessicate the fuel, and for a positive contribution of energy when and if the live material starts to burn (Albini 1976).

CURRENT PLANS

Three research work units at the Northern Forest Fire Laboratory in Missoula, one in East Lansing, Michigan, and one in Fort Collins, Colorado, have contributed research specifically directed at improving the NFDRS. We feel that significant progress has been made, and the improvements will be passed on to users in early 1978. For the next 12 months, a major effort will be made in training, in the publication of documenting and informational materials, and in the modification and development of supporting computer programs. Every effort will be made to minimize the impact of the changes on fire management organizations.

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An Application of Geosynchronous Meteorological Satellite Data in Fire Danger Assessment[1]

Marshall P. Waters, III[2]/

Abstract.--Synchronous meteorological satellite Visual and Infrared Spin-Scan Radiometer (VISSR) digital data are analyzed for surface temperature and cloud cover. These data are blended with conventional meteorological observations made at the surface. An automated technique is described that estimates the one-hour timelag fuel moisture (1-HR TLFM) component of the National Fire Danger Rating System (NFDRS). Comparisons with computed values taken at Fire Danger Stations in the study area are analyzed. The 1-HR TLFM can be estimated for selected meteorological conditions. Automated estimates of the 1-HR TLFM can be made hourly. Distribution of cloud cover can be monitored and mapped each half-hour from satellite visible (VIS) data to indicate surface insolation patterns.

INTRODUCTION

The knowledge of present, as well as antecedent, meteorological conditions is necessary in determining fire danger levels and predicting fire behavior. For the past several years, there have been efforts to provide more timely data for those variables that influence the level of fire danger. The Automated Forest Fire Information Retrieval and Management System (AFFIRMS) (Helfman, 1974) is an example of this. With this sytem, both the National Weather Service (NWS) and fire protection agencies input weather and forecast data into a time-sharing computer, thus providing more timely data to interested users. A more ambitious system to provide timely data, FIRESCOPE, will telemeter meteorological and fire danger parameters from a network of instrumented platforms in Southern California wildlands to a Synchronous Meteorological Satellite (SMS), then to a time-sharing computer data base.

Another source of timely meteorological data is that collected by the National Environmental Satellite Service (NESS) located at Suitland, Maryland. The VIS and thermal infrared (IR) digital data collected each half-hour from two geosynchronous meteorological satellites may be a valuable source of meteorological data not currently used in fire danger assessment. This paper describes an automated technique that uses both satellite and ground-based meteorological data to estimate the 1-HR TLFM component of the NFDRS. A forested area in the southeastern United States is used for the study area.

NATIONAL FIRE DANGER RATING SYSTEM (NFDRS)

The NFDRS was developed at Ft. Collins, Colorado, with initial research beginning in 1968. The system is described by Deeming, et al. (1972).

The NFDRS is a structured system using meteorological data (temperature, cloud amount, relative humidity, precipitation, windspeed), objective estimates (dead-fuel moisture), and subjective estimates (lightning risk, man-caused risk, slope, live-fuel moisture, fuel model) to predict forest fire behavior. This allows fire danger indexes of occurrence, fire load, and burning to be estimated, which, when summed, give a seasonal severity measure for the area of concern.

An accurate estimation of the fire danger level of a protected area depends on a valid fuel moisture and weather relationship. A meaningful estimate is difficult due to the

1/Paper presented at Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.
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complex nature of the forest fuel distribution patterns and the changing meteorological conditions.

The fuel moisture content is one of the major elements in evaluating the fire danger level, as well as predicting fire behavior. In the NFDRS, dead fuels have been classified by their moisture timelags as 1-, 10-, and 100-hour classes. These classes correspond to cylindrical fuels less than one-quarter inch, one and one-quarter to one inch, and one to three inches in diameter, respectively (Fosberg and Deeming, 1971).

One-hour timelag fuels consist of dead hubaceous plants and roundwood less than one-quarter inch in diameter. These fuels are so defined as they are found to lose 63 percent of the difference between starting and final moisture content after drying one hour with conditions of 80°F air temperature and 20 percent relative humidity. The uppermost layer of needles or leaves on the forest floor is also included in this class. The 1-HR TLFM is the moisture content of the one-hour timelag fuels expressed as a percent of the total weight. These fuels, to a large degree, determine whether a fire will start and spread given an ignition source. An estimate of 1-HR TLFM is in itself an assessment of the fire danger.

At fire danger observation stations, the 1-HR TLFM is computed from tables using air temperature, relative humidity, and cloud cover. In this study, the 1-HR TLFM is estimated using cloud-cover information from SMS, thermal IR from SMS blended with air temperatures made at NWS observation stations, and humidity measures made at NWS observation stations.

DATA SOURCES

During the period of this study, the SMS-1 (since replaced by GOES-1) was located in a near-circular orbit above the Earth at an altitude of about 36,000 km. Its geostationary position was such that it remained near zero degrees latitude and 75 degrees West longitude. A more-complete description of the GOES system is found in NOAA Technical Memorandum NESS 64 (Bristor, 1975).

The SMS spacecraft consists of a Visible and Infrared Spin-Scan Radiomter known as VISSR. The VISSR provides for high-resolution visible (1 km) and lower-resolution infrared (9 km) data. The NESS receives the VISSR digital data each half hour from SMS-1 (as well SMS-2 at 0°N and 135°W). The digital data are imaged and transmitted in picture format to various user communities throughout the United States.

For this study, the VISSR digitized data were collected on magnetic tape from SMS-1 for each half-hour during maximum heating from 1000 to 1600 LST over the study area (Figure 1). Five days in which the coastal area of southeastern Georgia was forecasted to be mostly clear were selected for study: January 2, 5, 14, 15, and 16, 1975. Mostly clear days were required to earth locate the the satellite data.

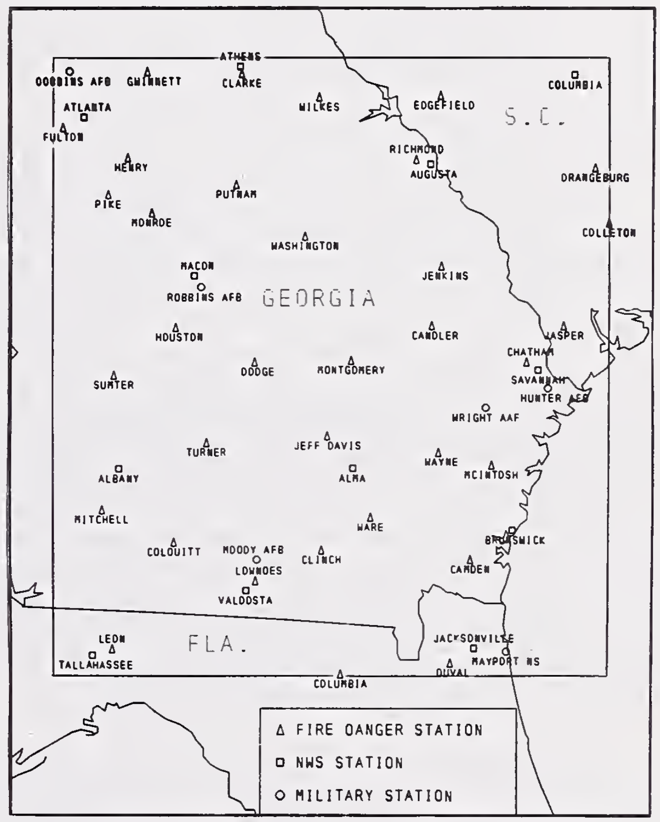

Figure 1. Location of the study area.

The hourly surface meteorological observations were collected from NWS, military, and flight service stations located within the study area. Meteorological data from these stations are transmitted hourly to the National Meteorological Center (NMC) also located at Suitland, Maryland. These coded weather observations become part of the data base used by NMC and retransmitted in different formats to other users. The data are available for recall from the NWS IBM 360/40 computer about 12 minutes after the hour. The hourly observations of those stations located in the study area were recalled from the computer and decoded for each hour from 1000 to 1600 LST for the days selected. Eighteen stations were used for this data source.

The ten-day Fire Danger and Fire Weather Records were used to obtain the fire danger and fire weather information of those stations located in the study area. These data were used to evaluate the estimation technique. Thirty-four stations were used for comparative purposes.

PROCEDURE AND METHODS

Digital visual data from SMS are a measure of the reflected radiation from the Earth scene. It is represented as a count value from zero (darkest) to 63 (brightest) and corresponds to zero and 100 percent earth albedo, respectively. Quantitative estimation of cloud amount over the study area is achieved by partitioning the frequency histogram of count values similar to that done by Miller (1971), but with a different number of partitions and weight values.

The study area was divided into 110 grid blocks. Each grid block was approximately 40-km square and contained 1600 count values representative of the earth albedo about 1-km square each. For clear conditions, the count values represent the albedo due to surface scene only. When clouds are present, the count values are that of albedo due to clouds. If cloud elements are smaller than the resolution of the sensor, then the count value represents an integrated value of the surface scene and the cloud. This also occurs when sampling is done at a cloud edge. When the surface scene and cloud count values are known, cloud amount can be estimated. The mean count value for each grid block was determined at different times of day under no-cloud condition.

Two threshold count values were selected for the area by time of day. The first threshold count value was selected on the basis of the mean value of the scene for the no-cloud condition. Any value at or below this mean count value (darker) was considered a cloud-free sample. The second threshold was selected such that a value at or higher than this value (brighter) was considered a cloud-covered sample. Count values between these two thresholds were considered to be 50 percent cloud-covered samples. Thus by weighting the count values, the percentage of cloud cover can be estimated. It is necessary to continually change the thresholds throughout the day because of the changing sun angle. This estimate of cloud amount for each of the 110 grid blocks was used as one of the elements necessary to estimate the 1-HR TLFM for that grid block.

In addition to cloud amount and humidity, 1-HR TLFM computation requires a measure of air temperature. To estimate air temperature over the study area, the following assumptions were made: (1) shelter temperature, as measured by NWS stations, varies linearly between stations; (2) the gradient values of the SMS-equivalent blackbody temperatures of the surface-emitted radiance values within the area are representative of the gradient field of air temperature; and (3) absorption of the infrared radiance by the atmosphere is the same over the area.

The infrared sensor of the SMS samples only a narrow wavelength radiation band from the surface within a limited field of view (4x8 km). For the wavelength band being measured, the sensor measures a quantity that is a function of the radiating surface emissivity and temperature of the radiating body.

For every SMS observation, each of the 110 grid blocks contains 50 infrared samples of emitted Earth radiances. As with the visible sensor, the infrared sensor either samples clear surface or cloud or a cloud/ground disposition dependent on cloud amount and pattern within each grid block. For clear targets, determination of surface temperature is relatively easy; however, partly cloud conditions are more difficult.

DETERMINATION OF SURFACE TEMPERATURE

The retrieval of surface-equivalent blackbody temperature for each grid block was attempted by an analysis of the frequency distribution of 50 radiance values within the block and from the estimate of cloud amount, as described above.

Analysis of the infrared data reduces to identifying certain infrared histogram types; thus, a valid decision concerning surface temperature data can be made. Clear and mostly cloudy grid blocks can be determined readily from the analysis of visual data. Even though analyses of partly cloudy grid blocks sometime contain valid surface temperature data, these data are much more difficult to analyze. This difficulty arises because the distributions of cloud amount, type, and patterns are virtually infinite in nature. As a result, a whole host of infrared histograms is evident from a given target size when clouds are viewed from satellite altitude.

The Pearson System (1894) of distribution classification is used to identify frequency distribution shapes for interpretation of the infrared data with grid blocks. Standard deviation, skewness, and kurtosis are computed for the sample of 50 discrete measures of infrared values in the grid block. The σ,

$\sqrt{b_1}$, and b_2 give an interpretation of the shape of the frequency distribution of the 50 values. Surface temperature retrieval decisions are made from this information as follows. All grid blocks containing 40 percent or more estimated cloud cover, as determined from the visual data within that block, were eliminated. The effect of cloud and cloud edges does not permit accurate retrieval with blocks containing 40 percent or more cloud cover. For grid blocks less than 40 percent cloud cover and standard deviations less than 2.0 counts values, the mode count value of the distribution is considered most representative of the surface value. For all other grid blocks, infrared distribution's position on the Pearson β_1,β_2 plane (Pearson and Hartley, 1972) was determined. Only those distributions indicative of surface view were then analyzed for warm mode values. In this study, warm modes of frequency distributions of partly cloudy scenes are considered surface-emitted radiances. Thus, using this frequency distribution classification technique, it is possible to automatically retrieve only surface values.

BLENDING SURFACE AND AIR TEMPERATURE FIELDS

In order to obtain a better spatial estimate of air temperature over the study area, the gradient field of equivalent blackbody surface temperatures is assumed to represent the gradient field of air temperature. The more dense measures of surface temperature and the relatively sparce measures of air temperature are then blended together to achieve a better estimate of air temperature over the field. This blending technique is described by Holl and Mendenhall (1971). Fields of data are blended by defining an error function that expresses the inconsistency between a gradient field and a measured field, and generating a new field that minimizes the error function over the whole field.

Successfully retrieved surface temperature from the grid blocks are placed in the center of the grid block and considered representative of that block. A grid mesh of 21x23 is placed over the study area. Surface tempeature values at each of the 483 grid intersections are computed by weighting nearby surface temperature observations, based on their respective distances to the grid intersection point. The NWS air temperatures were analyzed in this same manner. The gradient of the SMS surface temperature field is then determined at each point in the grid mesh and blended into the NWS air temperature at that point to get a new value. Thus, gradients of the SMS surface temperature field are reflected in the NWS air temperature analysis field.

ESTIMATED AND FIRE DANGER STATION 1-HR TLFM

The 1-HR TLFM estimate value is computed at each of the 483 grid points using SMS-blended air temperature, relative humidity from an estimated field taken from NWS observations, and cloud amount from that estimated by the visible data from SMS. Air temperature, humidity, and cloud amount, as observed by the 34 fire danger stations at 1300 LST, are placed at their respective locations in the study area. These data are then interpolated and weighted to the 21x23 grid mesh.

RESULTS AND DISCUSSIONS

If one considers the 21x23 grid mesh intersection points as a distribution of the 1-HR TLFM from the study area, then computed and estimated fields can be compared along with the differences between the fields. Table 1 compares these fields for the days selected.

Table 1.--Distribution statistics for calculated, estimated, and difference fields for 1-HR TLFM for 1300 EST of January 2, 5, 14, 15, 16, 1975.

Date	Distribution	$\overline{X}$	σ	Max	Min	$\sqrt{b_1}$	b_2	n
2	Calculated	5.47	0.90	10.2	3.3	2.92	12.13	483
	Estimated	4.78	1.07	10.2	3.7	1.45	5.65	483
	Difference	-.70	0.94	3.0	-5.9	-.27	8.57	483
5	Calculated	8.88	1.57	14.9	6.2	0.73	3.39	483
	Estimated	8.20	1.67	17.0	5.9	1.04	4.68	483
	Difference	-.68	1.22	5.7	-5.2	-.02	7.08	483
14	Calculated	6.63	0.96	10.9	4.4	1.17	5.60	483
	Estimated	5.96	0.56	7.6	4.7	0.15	3.01	483
	Difference	-.66	0.96	1.1	-4.7	-.94	4.29	483
15	Calculated	6.30	0.30	10.2	4.4	0.94	4.96	483
	Estimated	5.78	0.47	7.4	4.6	0.18	3.04	483
	Difference	-.52	0.67	2.1	-3.9	-.71	7.49	483
16	Calculated	6.61	1.63	11.4	4.0	0.91	3.42	483
	Estimated	6.22	1.20	10.5	4.7	1.90	6.32	483
	Difference	-.38	1.20	3.0	-4.1	-.25	3.28	483

Table 1 indicates that the estimated and computed fields are in good agreement. Since data from the SMS are available half-hourly and surface observations from NWS observations are available from NMC hourly, estimates of 1-HR TLFM could be made. A more detailed analysis of mapped hourly 1-HR TLFM distribution for this period can be found elsewhere (Waters, 1975).

Data from the SMS has been blended with surface meteorological data to estimate a component in the NFDRS. Results indicate generally good agreement. At the time this study was conducted, data had to be collected on magnetic tape and processed later after earth location. Today, automated earth-location techniques, used operationally, are accurate to about 10 km or better. Digital data from the SMS/GOES are now earth located and ingested into disk making the data available near real time. Only specific sequences of SMS/GOES data are now being ingested for an area 50°N to 18°S and 25°W to 135°W. Disk space has been made available to ingest all SMS/GOES thermal infrared (some visible also) digital data at reduced resolution (9 km). Techniques to automatically process the digital data for time sequence scene differences are now being developed at NESS.

The real value of the SMS/GOES data might not be that it can be molded to a conventional measure of fire danger assessment, but that some new product such as scene change temperature, cumulative cloud cover, or surface temperature change will be found not only practical but economical to produce. It is technically feasible to produce such products today since the NESS IBM 360/195 computer containing the VISSR real time data is connected to the NWS IBM 360/40 computer containing the surface observation data files. In addition to these data are the forecast fields produced by NMC. This author knows of no work within the U.S. Department of Agriculture, NWS, or NESS to develop such an automated product.

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Analysis of Colorado Mountain Fire Weather[1]

Jack D. Cohen[2/]

Abstract.--Surface data from fire weather stations were used to calculate ninetieth percentile Burning Indicies and defined as critical fire weather. High correlations were found between the occurrence of dry-wind conditions and the severity of critical fire weather. A synoptic 500 mb examination indicated a general trend for certain patterns to accompany regional winds. Analysis of gravity wave potential through the Scorer number indicated that high surface winds can be accompanied by moderate 500 mb winds with decreased atmospheric stability.

INTRODUCTION

Colorado is experiencing population increases, particularly in and adjacent to the east slope metropolitan areas. The increase in population is also being felt in the forested mountain areas by means of permanent residences, resorts and short-term visitation such as weekend camping and hunting in the autumn. Although in other regions, the increased investments and use has created a potential for destructive fire occurrences.

Land management plans have come into being in response to the increased utilization of Colorado mountain areas. To provide for a complete land management plan, the potential destruction from wildfire should be considered. Such planning would indicate high hazard areas and thus help to avert high investment losses and possible loss of life. An analysis of the meteorology and climatology is essential for assessing the potential for the occurrence of a destructive wildfire.

1/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, Nov. 16-18, 1976. From a thesis submitted to the Graduate Faculty of Colorado State University in partial fulfillment of the requirement for the degree of Master of science. This research was supported by the Eisenhower Consortium for Environmental Forestry Research and is published as Eisenhower Consortium Report No. 15.

2/ Research Forester, Intermountain Forest and Range Experiment Station.

GENERAL METHODS

Data for the analysis were acquired from the Forest Service for Colorado fire weather stations. Only those stations with at least 8 years of historical records were chosen. Figure 1 gives a list and distribution of the fire weather stations. All of the surface analysis was done using these weather stations. Synoptic maps and Grand Junction upper-air data were acquired from the Daily Weather Map series (U.S. Dep. of Commerce) and the Northern Hemisphere Data Tabulations (U.S. Dep. of Commerce).

Surface data from fire weather stations were used to calculate National Fire Danger Rating System (NFDRS) (Deeming and others 1972) Burning Index (BI) values by means of FIRDAT (Furman and Helfman 1973). The NFDRS fuel models used for the BI calculations were the same for the stations as those used by the regional dispatcher. The BI was selected as an indicator of the relative severity of fire weather because of its comprehensive integration of the System's weather inputs.

A ninetieth percentile Burning Index level was calculated for the historical record of each selected weather station. Those BI values above the ninetieth percentile level were considered indicative of severe weather conditions for their respective station and defined as critical fire weather.

The occurrence of low relative humidities and high windspeeds (dry-wind conditions) were tabulated from the historical record for each station. From this tabulation, a percent occurrence of the dry-wind conditions was found during a time experiencing a BI above the

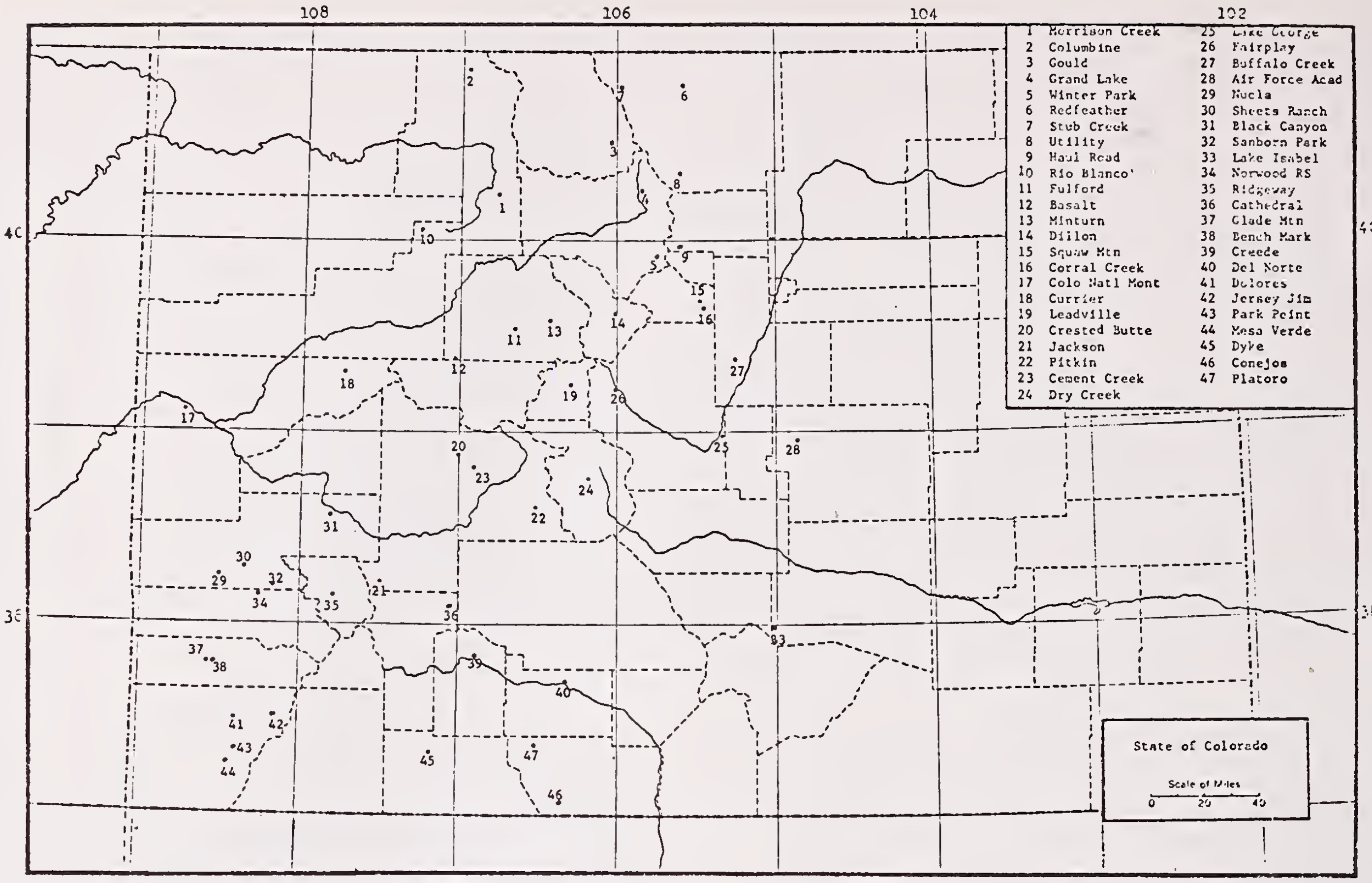


Figure 1.--Colorado station location map.

ninetieth percentile level.

Those periods experiencing critical fire weather (ninetieth percentile BI) were analyzed for their accompanying synoptic patterns. The general flow was characterized using the 500 mb level. Grand Junction upper-air data (1200 Z) were analyzed for the period May through September 1968 for recurring gravity wave characteristics accompanying windy conditions experienced at Colorado fire weather stations.

ANALYSIS AND RESULTS

The ninetieth percentile boundary BI values for the selected fire weather stations were stratified according to the station's NFDRS fuel model. The BI values were ranked from highest to lowest and three relative severity levels were assigned to the ranking (high, medium, and low). This procedure normalized the BI values between the different fuel models. The BI boundary value with its respective severity ranking is shown in figure 2. Also plotted on the map are fire climate-fire weather forecast zones based on equilibrium moisture content (e.m.c.) (Fosberg and Furman 1973). The BI severity varies greatly within each e.m.c. climatic zone. This does not contradict the placement of the e.m.c. climatic zones; rather, it indicates that fuel moisture does not dominate in determining the severity of the ninetieth percentile BI in Colorado mountain areas.

Dry-wind conditions were chosen to be tested for their contribution to the ninetieth percentile BI severities. The conditions are as follow:

Relative Humidity	Windspeed
$\leq$20 percent	>7.5 meters/sec
$\leq$30, >20 percent	>10.0 meters/sec
$\leq$10 percent	>5.0, $\leq$7.5 m/sec

The dry-wind conditions were not chosen from severe weather that was experienced at the weather stations. These conditions will always increase the BI when entered as input into the NFDRS. However, high Burning Indicies are not solely dependent on the occurrence of the conditions above. The fact that the dry-wind conditions are severe is obvious; their contribution to the ninetieth percentile BI severities and thus critical fire weather is not obvious.

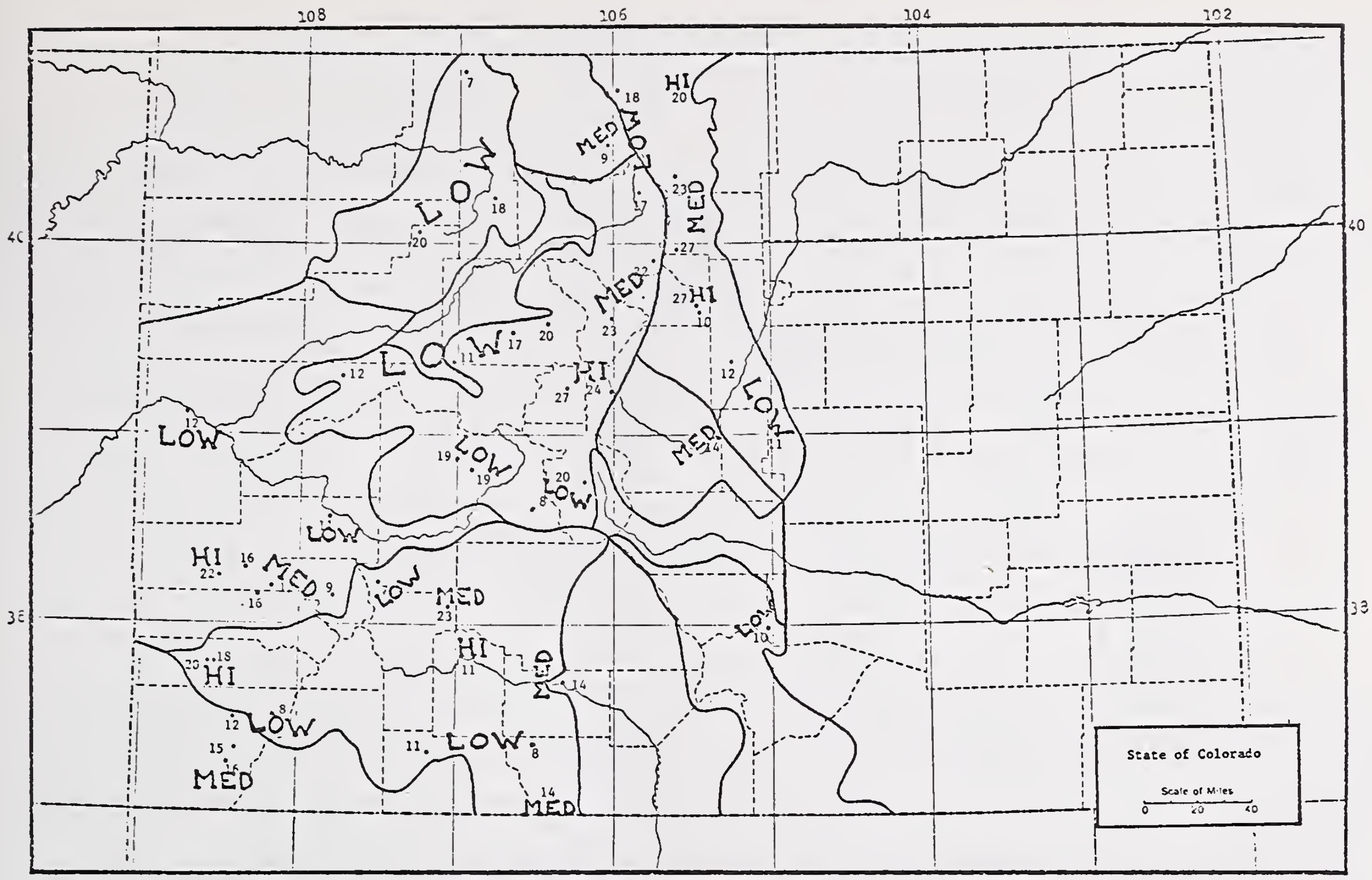


Figure 2.--Map of Colorado regional Burning Index severities with e.m.c. zones.

Table 1 lists, by representative fuel model, the ninetieth percentile BI boundary value with its respective percent dry-wind contribution. The ninetieth percentile BI boundary value was then correlated with the dry-wind percent contribution to critical fire weather, resulting in high correlation coefficients. This indicates that the severity of BI values in Colorado are dependent on dry-wind conditions. This characterizes Colorado critical fire weather as a dry-wind phenomenon.

The establishment of the dependence of critical fire weather in Colorado on dry-wind conditions was followed by an examination of the relative importance of each component (low relative humidity and high windspeed). Frequencies of occurrence for relative humidity intervals and windspeed intervals were plotted on a map with the relative BI severities. Relative humidity frequencies did not correspond spatially with the distribution of BI severities. This should not be surprising since fuel moisture was shown not to be indicative of ninetieth percentile BI severities through the comparison with e.m.c. zones. Windspeed frequency of occurrence did correspond to the distribution of BI severities. Figure 3 illustrates the association of high windspeed frequencies with those areas having high severity ninetieth percentile BI's. It

Table 1.--Critical Burning Index with percent wind contribution

Fuel Model C

Station	90% BI	% Dry-wind
Nucla	22	92.5
Redfeather	20	79.9
Glade Mtn	20	66.3
Bench Mark	18	73.1
Sheets Ranch	16	31.6
Norwood	16	49.6
Mesa Verde	16	26.8
Park Point	15	13.8
Lake George	14	32.5
Del Norte	14	30.6
Conejos	14	24.6
Buffalo Crk	12	7.8
Colo Natl Mont	12	16.1
Sanborn Park	12	23.9
Dolores	12	3.4
Currier	12	2.9
Air Force Acad	11	8.2
Black Canyon	11	4.1
Dyke	11	2.2
Basalt	11	8.3
Lake Isabel	10	6.4

(90% BI - % Dry-wind correlation)
r = .91

Fuel Model G

Station	90% BI	% Dry-wind
Haul Road	27	62.3
Squaw Mtn	27	61.2
Leadville	27	53.4
Fairplay	24	39.3
Utility	23	17.0
Cathedral	23	24.5
Dillon	23	8.3
Winter Park	22	13.4
Rio Blanco	20	5.3
Minturn	20	3.6
Dry Creek	20	15.4
Crested Butte	19	4.5
Cement Creek	19	8.5
Morrison Crk	18	0.0
Stub Creek	18	0.0
Fulford	17	6.4
Grand Lake	17	1.3

(90% BI - % Dry-wind correlation)
r = .94

Fuel Model H

Station	90% BI	% Dry-wind
Creede	11	45.7
Corral Creek	10	30.3
Gould	9	8.6
Ridgeway	8	6.8
Jersey Jim	8	5.1
Platoro	8	7.8
Pitkin	8	9.1
Columbine	7	0.0
Jackson	7	0.0

(90% BI - % Dry-wind correlation)
r = .94

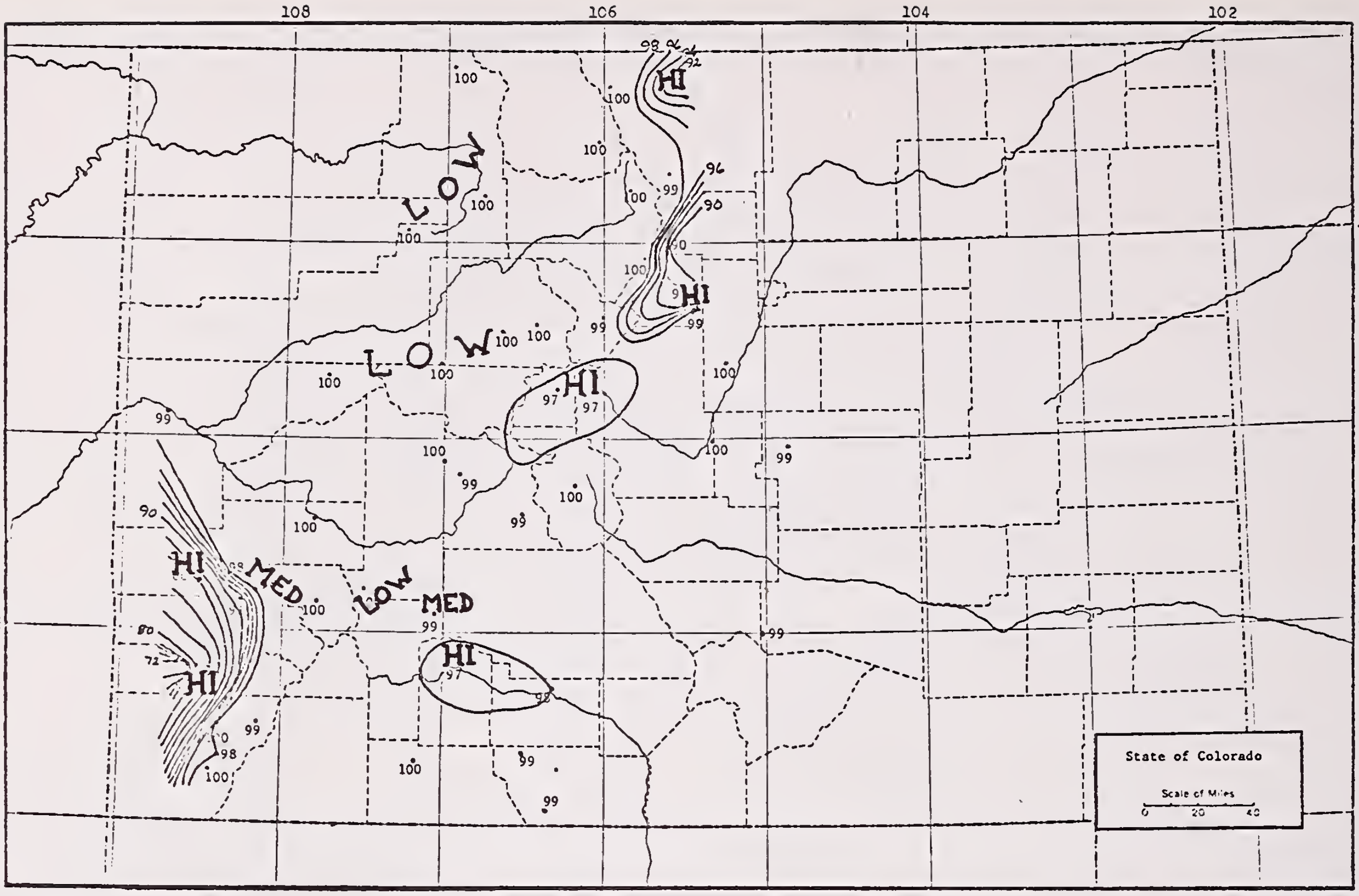


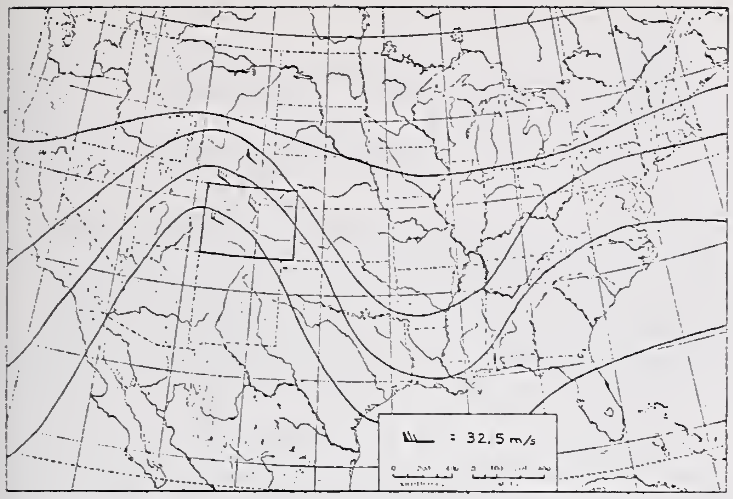
Figure 3.--Comparison of wind frequency and critical BI severity in Colorado (wind, 10 m/s; contour interval, 2 percent; HI, MED, LOW refer to severity of BI).

should be noted that the areas of high severity also experience relatively high frequencies of low relative humidities. This is not a contradiction. Several areas having relatively high frequencies of low relative humidities, but experiencing little wind, possessed low severity BI's.

The examination of surface winds in relation to critical fire weather also indicated regional tendencies for windiness. The windy areas on the west slope and east slope of the mountains (shown in fig. 3) did not experience high wind conditions simultaneously. Synoptic, 500 mb level patterns were examined for each occurrence of a wind, 10 meters per second or greater, with an accompanying relative humidity less than or equal to 20 percent. Low relative humidity criteria were included to help filter out convective storm activity. Composite maps were drawn up to represent the generalized 500 mb level patterns that accompany high wind-low relative humidity conditions at the fire weather stations.

Figures 4 and 5 depict the generalized 500 mb patterns that accompany high winds along the northern Front Range. These patterns are characterized by anti-cyclonic curvature over Colorado, producing rising barometric pressure and generally clear skies. Usually these winds do not extend south over the entire state, but when they do, high mountain stations will experience high wind conditions. High winds in the mountains on the west slope are usually accompanied by cyclonic circulations and decreasing barometric pressure. Figures 6 and 7 depict winds accompanied by low pressure systems to the west of Colorado. The direction of the wind in the southwest quadrant is dependent on the north-south location of the trough. Figure 8 depicts southwesterly winds accompanied by a ridge over the midwest.

One prominent exception to the above descriptions was evident during the pattern analysis. Several high wind situations at many of the stations were not accompanied by significant 500 mb winds. The 500 mb patterns were not generally well defined and exhibited windspeeds as in figure 8. The influence of atmospheric stability on surface winds was examined by a general gravity wave characterization.



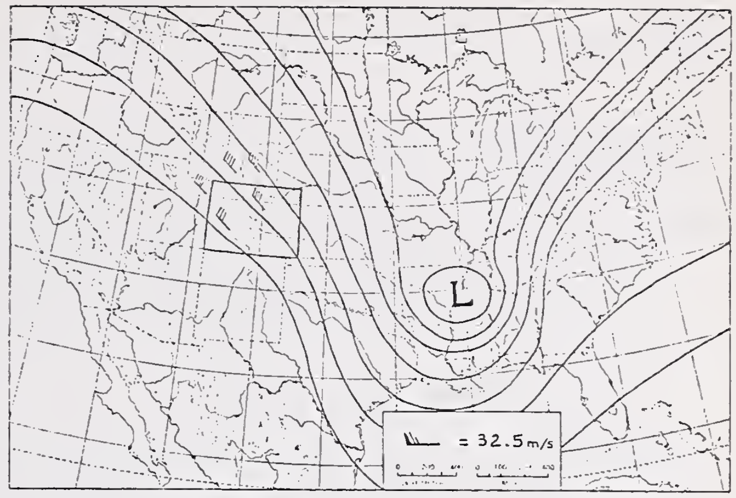
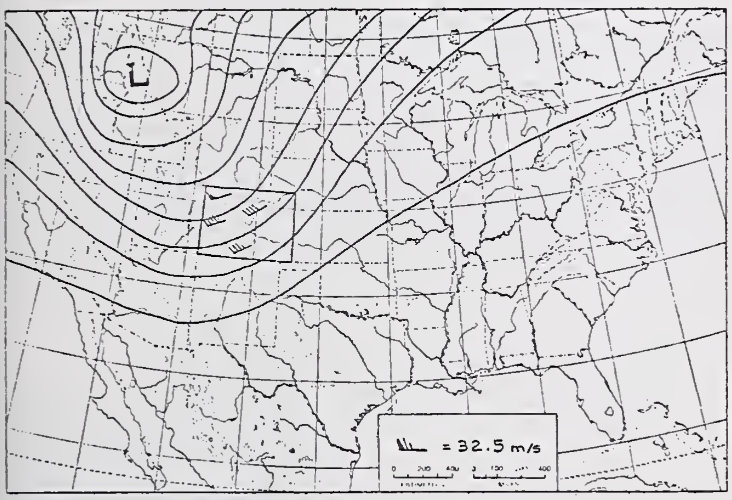


Figure 4.-- Figure 5.--
500 mb maps of patterns associated with high winds in northern Colorado.



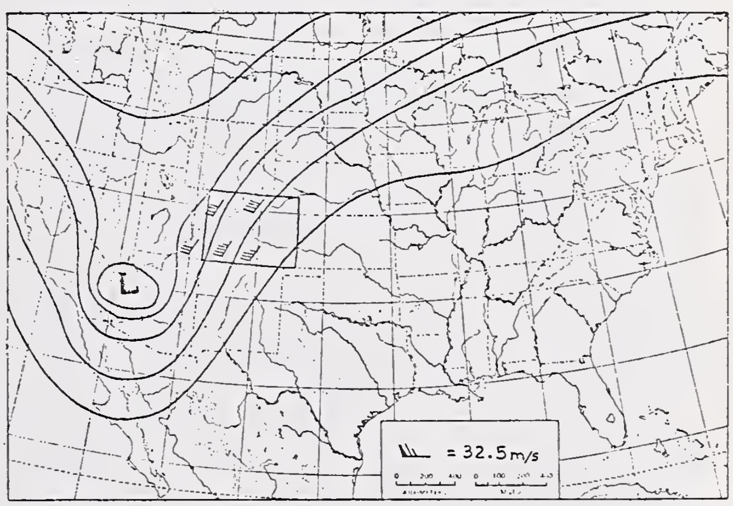


Figure 6.-- Figure 7.--
500 mb maps of patterns associated with high winds in west-slope mountains of Colorado.

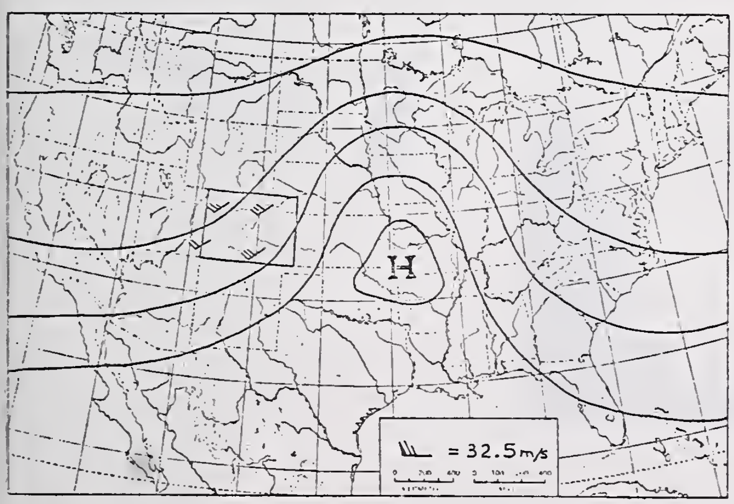


Figure 8.--500 mb map of pattern associated with high winds in west-slope mountains of Colorado.

Grand Junction upper-air data were analyzed for its general gravity wave character using Scorer's wave number (Scorer 1967):

$$\ell = \sqrt{\frac{g/\theta \frac{\delta\theta}{\delta z}}{u^2}}$$

where

ℓ = wave number (m^{-1})

θ = potential temperature (° K)

z = height (m)

u = wind velocity (m/sec)

g = acceleration due to gravity (m/sec^2).

Calculations were made using this modified finite form:

$$\ell^2 = \frac{g/\overline{\theta}\frac{\Delta\theta}{\Delta z}}{u^2}$$

where

ℓ = (wave no.)^2 for the atmosphere between 700 mb and 300 mb

$\overline{\theta}$ = average potential temperature between 700 mb and 300 mb

$\Delta\theta$ = potential temperature difference between 700 mb and 300 mb

Δz = height difference between 700 mb and 300 mb

u = 500 mb windspeed.

The equation (ℓ^2) behaves as follows:

ℓ^2 is inversely proportional to the windspeed; if the atmosphere becomes stable;

$\frac{\Delta\theta}{\Delta z}$ increases, thus increasing ℓ^2.

As the atmosphere becomes less stable,

$\frac{\Delta\theta}{\Delta z}$ decreases, thus decreasing ℓ^2.

At neutral stability, $\frac{\Delta\theta}{\Delta z} = 0$, $\ell^2 = 0$.

As ℓ^2 increases, wavelengths decrease causing less disturbance to other portions of the atmosphere. Momentum is usually not transferred to the ground. As ℓ^2 decreases, wavelengths increase, increasing the possibility of a momentum transfer to the ground.

An ℓ^2 value was calculated for each 1200 Z sounding from June through September 1968. The dry-wind classes previously defined, excluding windspeeds less than 7.5 meters/sec, were used to determine the occurrence of a high wind at any of the fire weather stations for each day.

The occurrences of ℓ^2 values are plotted with the high wind occurrences in figure 9. This figure indicates an important relation between high wind occurrence and ℓ^2 values between 1.0×10^{-7} and 5.0×10^{-7}. The high wind occurrences are not surprising when ℓ^2 is in this interval because high winds at 500 mb contribute to a low ℓ^2. However, 5

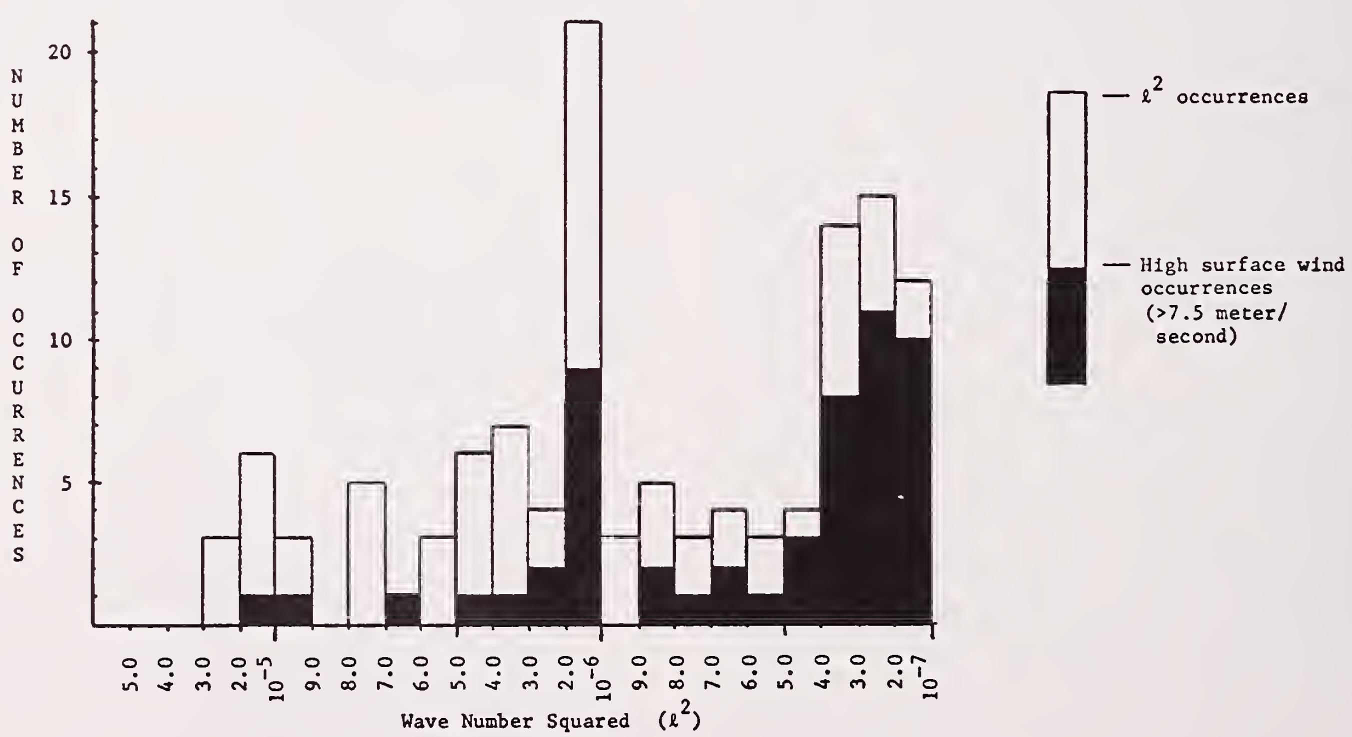


Figure 9.--ℓ^2 interval occurrences with the occurrence of high surface winds by ℓ^2 interval.

out of 19 high wind occurrences with ℓ^2 values between 2.0×10^{-7} and 4.0×10^{-7} were accompanied by moderate 500 mb winds (12.5 meters/sec). In these cases, a decrease in stability resulted in low ℓ^2 values, longer wavelengths, and accompanying high surface winds.

SUMMARY AND CONCLUSIONS

The ninetieth percentile BI level was calculated from the historical record for each station and defined as critical fire weather for that station. The stations were ranked according to their relative severity of ninetieth percentile BI and compared with their respective equilibrium moisture content (e.m.c.) zones. A lack of correspondence indicated that the ninetieth percentile BI severity was not highly dependent on fuel moisture.

Dry-wind conditions were defined and their frequency of occurrence found to be highly correlated to the ninetieth percentile BI severity. The regional distribution of dry-wind occurrences corresponded with the ninetieth percentile BI severity distribution. The distribution of high wind occurrences also corresponded with the relative severities of the ninetieth percentile BI, thus indicating the importance of wind in producing critical conditions in Colorado.

The 500 mb pattern examination indicated that east slope winds are generally accompanied by flows north of west, whereas west slope winds are generally accompanied by flows south of west. Usually the high surface winds were accompanied by well developed 500 mb patterns and strong input winds. However, in several cases, strong surface winds were accompanied by only moderate 500 mb winds and poorly defined patterns.

Examination of the data from one season, using Scorer's wave equation, indicated that in several cases a long wave character can be induced through less stable conditions and moderate winds. This tends to explain how high surface winds can be experienced from only moderate winds aloft.

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Synoptic Study of the Meteorological Conditions Associated with Extreme Wildland Fire Behavior[1]

Edward A. Brotak and William E. Reifsnyder[2]/

Abstract.--Fifty-two major wildland fires in the eastern half of the United States were analyzed to determine the synoptic situations involved. At the surface, 3/4 of the fires were found near frontal areas. The vast majority of fires were associated with the eastern portion of small amplitude but intense short wave troughs at 500 mb. A lack of moisture advection at 850 mb prohibits precipitation which normally accompanies these systems. This lack of precipitation in association with strong low-level winds found in these regions produces dangerous fire conditions at the surface. Such situations are shown to occur rarely.

INTRODUCTION

A small percentage of all wildland fires become major fires and are responsible for many of the lives lost and most of the resource damage. Besides favorable fuel moisture conditions, certain infrequent combinations of surface weather conditions are a prerequisite on the day of the fire. The major objective of this research is to determine the synoptic weather situations associated with these fires. In this study, we have determined the upper-air conditions that appear to be necessary for the development of large (>5000 acres) wildland fires in the eastern portion of the United States.

A review of the literature indicated that major fires were often associated with surface frontal areas. Such fires were reported both ahead of and behind cold fronts by Bond, et al. (1967), DeCoste, et al. (1968), Luke (1971), Miller (1972), Sando and Haines (1972), Sullivan (1966), and Wade and Ward (1973). Only a few researchers examined the upper air conditions and, of these, Bond et al. (1967), Finklin (1973), and Pirsko et al. (1965), noted an upper trough over the surface fire area. It should be noted here that in the past most researchers have only examined one fire and its attendant situation. We believe that the present study is the first attempt to analyze comprehensively the synoptic patterns associated with a large number of fires widely separated in time and space. Schroeder (1964) did an extensive study in this area, but he dealt mainly with air mass type and only with periods of high fire danger, not actual fire occurrences.

DATA

Fire data were provided by the state fire officials and consisted of all fires burning 5,000 acres or more in the eastern half of the United States from 1963-1973 (See Table 1 and Figure 1). Information for each fire included the dates of fire start and control, location, and acreage burned. Of particular concern were major fire runs, periods of time when the fire was probably uncontrollable due to the prevailing weather conditions.

Weather maps for these periods were provided by the National Climatic Center in Asheville, North Carolina. Surface maps were available every three hours for the fire period. Morning and evening standard pressure level maps at 850 and 500 mb (~ 1500 and ~5000 m respectively) were also available.

1/Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, Nov. 16-18, 1976.

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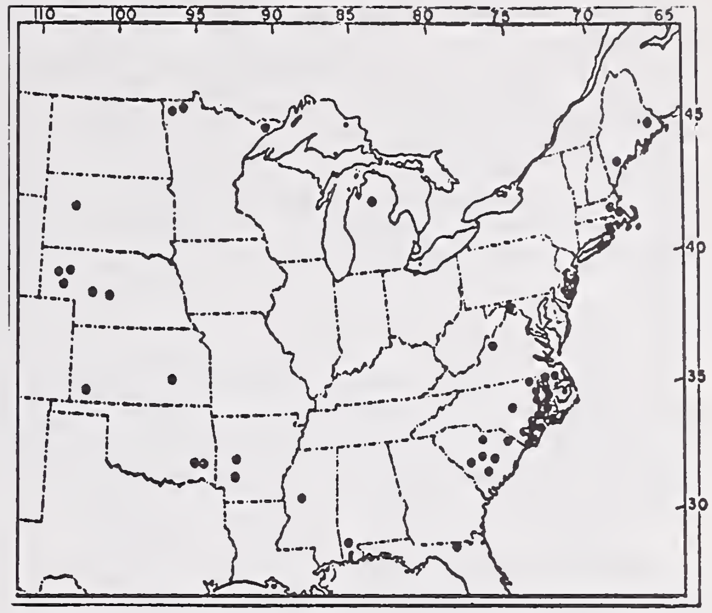
Table 1.--List of all fires analyzed.

Date	Location	Acreage Burned
3/25/63	Oklahoma	14,200
4/4/63	North Carolina	23,200
4/4-5/63	North Carolina	15,300
4/4-5/63	North Carolina	13,900
4/4-5/18/63	North Carolina	37,000
4/4/63	North Carolina	44,200
4/4-5/63	North Carolina	7,100
4/4-5/63	North Carolina	6,200
4/20/63	New Jersey	76,000
4/20/63	New Jersey	14,000
4/20/63	New Jersey	11,300
4/20/63	New Jersey	33,400
4/20/63	New Jersey	12,800
4/20/63	New Jersey	14,500
4/20-21/63	West Virginia	6,600
4/23-26/63	North Carolina	26,500
10/30/63	Arkansas	13,700
3/15/64	Oklahoma	7,200
5/23-25/64	Massachusetts	5,500
9/17-24/64	New Jersey	5,200
4/13/65	North Carolina	5,000
5/5/65	Nebraska	20,000
8/4-8/65	Maine	12,100
12/5-10/65	Arkansas	6,000
3/31-4/3/66	South Carolina	8,300
4/1-2/66	South Carolina	7,400
4/1/66	South Carolina	5,100
4/1-4/66	South Carolina	6,000
4/1-10/66	North Carolina	5,800
4/1-5/66	North Carolina	17,000
4/2-6/66	South Carolina	5,500
4/1-7/67	North Carolina	9,400
4/2-4/67	North Carolina	5,100
4/3-4/67	North Carolina	8,000
4/18-21/67	South Carolina	6,000
5/8-13/69	North Carolina	14,700
2/9-10/70	Alabama	6,000
12/4-5/70	North Carolina	6,300
1/18/71	Nebraska	9,200
3/22-23/71	North Carolina	29,300
4/12-15/71	North Carolina	5,800
4/18/71	New Jersey	21,000
4/18-21/71	North Carolina	14,400
5/14-16/71	Minnesota	14,600
2/26/72	Nebraska	7,200
2/28/72	Nebraska	5,600
3/6-7/72	Nebraska	120,000
3/6-7/72	Kansas	8,500
3/19/72	Kansas	9,000
4/16-18/72	North Carolina	18,500
4/11-13/73	Minnesota	7,700
4/12-15/73	Minnesota	9,200

Figure 1.--Location of all fires.



ANALYSIS

Surface Synoptic Situation

The fire runs were categorized by surface synoptic situation and the results are shown in Table 2. The fires were located with respect to an idealized frontal system and plotted in Figure 2. As shown in Table 2, more than half of all fire runs occurred following the passage of a dry cold front. Most runs occurred in the southeastern section of the frontal region (fig. 2). It is apparent that this is the primary region in which the proper combination of wind, moisture, temperature, and fuel conditions are found to produce large-fire conditions in the eastern half of the United States.

One-quarter of the runs occurred prior to the passage of a cold front. Often a fire would make a run both ahead of and behind the front. Thus, three-quarters of the fire runs were frontal situations.

Twelve percent of the fire runs occurred in the warm sector of a low pressure area. There were two different types of low pressure areas involved with major fires. One was the Rocky Mountain low which produced dangerous fire conditions in the Plains and Midwest states. The other kind of low was a storm which moved easterly through southern Canada producing dangerous fire conditions in the Great Lakes states and in northern New England. Major lows in the eastern United States are almost always accompanied by precipitation.

Of the remaining fire runs, 5% occurred in the warm sector of a high pressure area far from any fronts or low pressure areas. Usually, these were continental tropical air masses with very high temperatures and extremely low

humidities. Four fire runs occurred with other synoptic situations.

Table 2.--Percentage of fire runs by synoptic situation.

Synoptic situation	# of runs	%
Following cold frontal passage (CFA)[1]	45	54
Prior to cold passage (CFB)[2]	20	24
Warm sector of low (WSL)[3]	10	12
Warm sector of high (WS)[4]	4	5
Other	4	5

1/CFA: Cold frontal passage in prior 24 hours, area not within closed cyclonic isobars.

2/CFB: Cold frontal passage occurred within 24 hours, area not within closed cyclonic isobars.

3/WSL: Area within closed cyclonic isobars with low pressure center to west, no cold frontal passage within 24 hours.

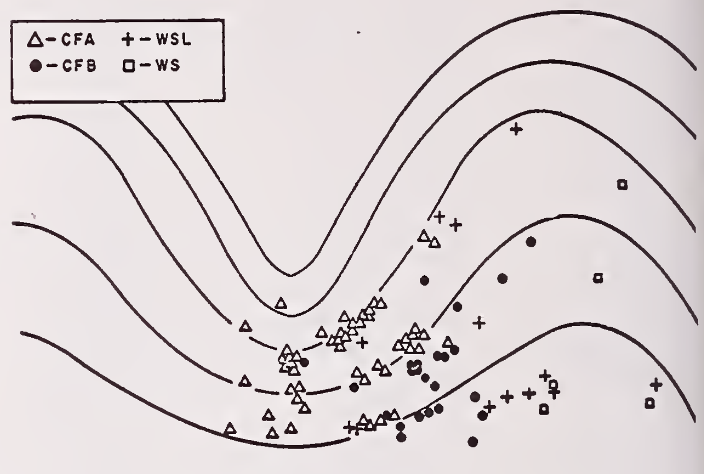
4/WS: Area within closed anti-cyclonic isobars with high pressure center to south or east, no cold frontal passage within 24 hours.

Figure 2.--Idealized surface map showing all fire runs.

500 mb Analysis

Figure 3 shows the location of the fire runs in relation to an idealized 500 mb (~5500 m) trough. The vast majority occurred in the southeastern portion of the trough. In most cases, small amplitude, intense, often fast-moving short wave troughs were involved. Usually the radius of curvature was small, 640 km or less. This great curvature induces more divergence aloft, thus intensifying the surface systems.

Figure 3.--Idealized 500 mb map showing all fire runs.



850 mb Moisture Advection

The analysis of the 500 mb flow patterns indicated that situations associated with major fires were similar to ones that usually produce precipitation and poor fire conditions. The reason for the lack of precipitation just prior to and during these extreme fire situations is very important in the overall understanding and especially for the prediction of extreme fire behavior. The precipitation process in the atmosphere has two components: There must be significant moisture in the air and there must be the dynamic process to produce condensation and precipitation. It appears that the dynamic processes occurred in many fire situations, so the atmospheric moisture content was examined.

A parameter often used in the routine forecasting of precipitation is moisture advection at 850 mb. If the dewpoint depression of the air at this level upwind of an area is 5°C or less, precipitation is likely if the synoptic situation favors it. Moisture advection at 850 mb was then examined for all fire runs, and in 93% of all cases, it was insufficient to allow precipitation. Thus, this was seen as a major factor associated with the development of large fires.

Moisture advection depends primarily on wind flow patterns: A source of moisture must be available for moisture to be advected. For areas in the eastern United States, the two major sources of moisture are the Gulf of Mexico and the Atlantic Ocean. The lack of moisture advection at 850 mb for most fire runs was due to a basic westerly flow at this altitude. Flows with a more southerly or easterly trajectory were not favorable for fire runs.

The reason for this flow pattern at lower

levels can again be traced back to the upper-air flow patterns. It was mentioned that the majority of upper-level troughs involved with extreme fire behavior were of small amplitude. Often, the trough was centered in Canada, but the lack of latitudinal extent prohibited the development of a long southerly flow which would pull up moisture from the Gulf of Mexico. The surface reflection of this upper-air flow is that the cold front often moves in from the north or northwest rather than west.

Frequency of Upper-Level Trough Passages

The association of major fires and upper-level trough occurrences would be meaningless if such occurrences happened every day. To determine a normal frequency of trough passages, two years were examined. The first year, 1973, produced ample precipitation over the eastern half of the United States especially in the spring, and only two major fires in Minnesota were reported. The second year, 1963, was noted for the drought along the East Coast and resultant fires in the spring.

Table 3 shows that in 1973, there were 89 upper trough passages, or about one every four days. In 1963, a drought year, there were 87; so the frequency was the same. Of greater importance is the passage of upper troughs without precipitation. These are the situations which were associated with most of the extreme fire occurrences. Such situations are very rare. Only five cases occurred in 1973. Surprisingly, only six cases occurred in 1963. Thus, the upper-air conditions seen associated with major fires in this study, i.e. dry trough passages, occur infrequently.

Table 3.--Frequency of upper-level trough passages.

	1963	1973
Total trough passages:	87	89
Total trough passages March-May:	21	25
Total trough passages without precip.:	6	5
Total trough passages without precip. March-May:	4	0

Related Surface Conditions

The synoptic situations discussed above are related to certain surface weather conditions which are characteristic of dangerous fire weather. The lack of precipitation is an obvious factor and has already been noted. The other prevalent factor was strong surface winds. Such winds were noted with almost all major fire occurrences.

SUMMARY

The occurrences of major fires in the eastern half of the United States have been related to certain specific synoptic situations. Most fires occurred near frontal areas, especially following the passage of a dry cold front. Such situations could be easily determined on surface maps and could be useful in forecasting.

Of even more importance to forecasting is the relationship between major fires and the upper-air situation. Major fires were associated with a specific type of 500 mb trough, an intense system of small latitudinal extent. Such troughs are associated with areas of strong winds but no precipitation at the surface, i.e. dangerous fire conditions. With the great accessibility of forecasts and high level of predictability of 500 mb, dangerous fire conditions could be reasonably forecast up to 72 hours in advance.

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The Effect of Latitude and Season on Index Values in the 1977 NFDR System[1]

Robert E. Burgan[2/]

Abstract.--Seasonal changes in day length and solar radiation intensity at three latitudes influenced the Man-Caused Ignition Component, the Energy Release Component, and the Burning Index of the National Fire-Danger Rating System. Seasonal effects for the Energy Release Component are greatest in fuel models with heavy loadings of large, dead fuels. Day length has little effect on the Man-Caused Ignition Component, but solar radiation intensity produces a small effect through its influence on fuel temperature. Inclusion of rate-of-spread in Burning Index computations reduces these effects.

INTRODUCTION

Fire managers have suggested that the National Fire-Danger Rating (NFDR) System should include the effect of seasonal changes in day length and solar radiation intensity. This refinement does influence the fire-danger indexes and will be in the 1977 NFDR System.

Seasonal changes in day length and solar radiation differ considerably from southern to northern latitudes. During the 6 months of the year from May 1 to October 31, the maximum interval from sunrise to sunset, at 34° latitude, is 14 hours, 26 minutes; the minimum interval is 10 hours, 50 minutes. During the same 6-month period, the interval from sunrise to sunset at 65° latitude, varies from 22 hours, 3 minutes to 7 hours, 57 minutes. Assuming that 67 percent of the radiation received at the top of the atmosphere actually reaches the earth, the intensity of solar radiation received by the earth's surface at solar noon during the May 1-October 31 period ranges from 1.26 to 0.68 calories per square centimeter per minute at 35° latitude, and from 0.84 to 0.04 calories per square centimeter per minute at 65° latitude. These differences in day length and radiation intensity should produce rather large differences in the NFDR indexes, particularly in the northern latitudes. However, the research reported here showed local weather modifies these effects to a great extent.

Weather data from three locations were used for the analysis: Lytle Creek Ranger Station at about 34° latitude in California's South Coast Drainage; Libby at 48° latitude in northwestern Montana; and Fairbanks Airport at 65° latitude in Alaska.

The NFDR indexes investigated were the Man-Caused Ignition Component (MCIC), an index proposed for the 1977 NFDR system, and related to the probability that a reportable fire will result if a "typical" man-caused firebrand encounters fine fuel; the Energy Release Component; and the Burning Index.

Fuel Model G, which has a high proportion of dead-to-live fuels, was used in the computations to generate these indexes.

MAN-CAUSED IGNITION COMPONENT

The MCIC is primarily dependent upon the moisture of fine fuels (1-hour timelag (1 HRTL) class fuels). These fuels consist of dead herbaceous plants and roundwood less than one-fourth inch in diameter. Also included is the uppermost layer of needles or leaves on the forest floor. Because this material responds so quickly to changes in temperature and relative humidity, its moisture content is influenced much more by the intensity of solar radiation at the basic observation time, than by long-term seasonal effects. The basic observation time is the time established to take the fire-danger observation which rates the day. It is generally in the early afternoon.

1/ Paper presented at the Society of American Foresters-American Meteorological Society Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, November 16-18, 1976.

2/ Research Forester, Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 507 25th Street, Ogden, Utah 84401. Located at the Intermountain Station's Northern Forest Fire Laboratory, Missoula, Montana.

MCIC values for the three locations were computed with radiation intensity values only for July 15, and compared with MCIC computations including radiation intensity calculated for each day in the study period. The results, for each of the three sample locations, are shown in figures 1, 2, and 3.

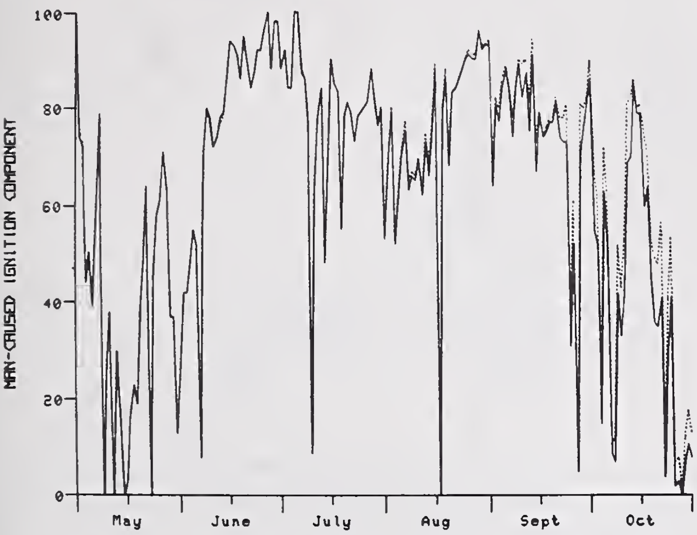

Figure 1.--Man-Caused Ignition Component computed for Lytle Creek (1974 data), with solar radiation intensity values for each day in the period (solid lines) and with intensity value for July 15 only (dotted lines).

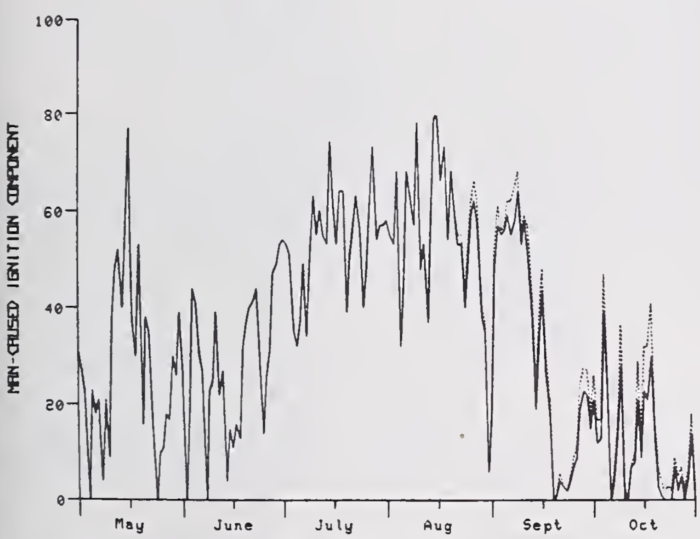

Figure 2.--Man-Caused Ignition Component computed for Libby (1973 data), with solar radiation intensity values for each day in the period (solid lines) and with intensity value for July 15 only (dotted lines).

The July 15 solar radiation intensity value becomes an increasingly poorer estimate of the actual value as one proceeds in time from that date. Thus, without the daily solar radiation correction, the MCIC becomes increasingly higher than it should in the fall portion of the fire season.

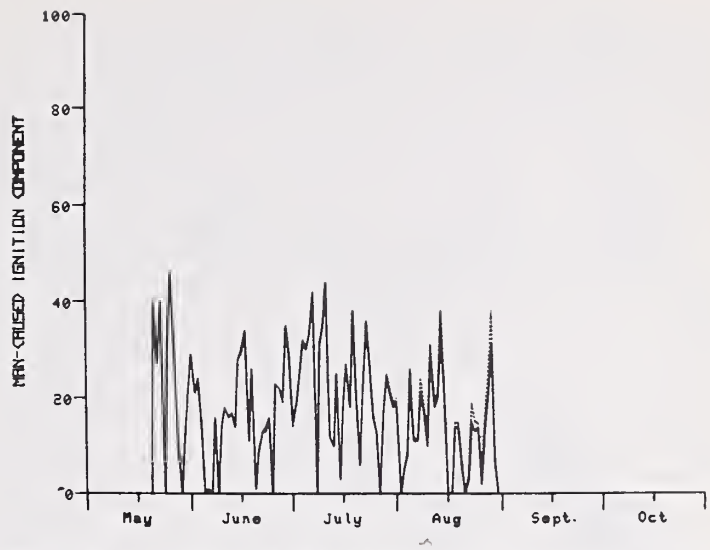

Figure 3.--Man-Caused Ignition Component computed for Fairbanks (1975 data) with solar radiation intensity values for each day in the period (solid lines) and with intensity value for July 15 only (dotted lines).

ENERGY RELEASE COMPONENT

Because the Energy Release Component of the NFDR is strongly influenced by larger fuels (100- and 1,000-HRTL classes), cumulative, seasonal weather effects on moisture contents become much more important than specific weather conditions at or near any particular basic observation time.

The moisture content of 100- and 1,000-HRTL fuels is a function of the equilibrium moisture content (EMC)[3] computed for early afternoon (maximum temperature-minimum relative humidity) conditions, early morning (maximum relative humidity-minimum temperature) conditions, and precipitation duration. Because the effect of precipitation duration is less than the effect of relative humidity during the fire season, the EMC exerts a strong influence on the moisture content of large, dead fuels.

EMC's were computed for both the early afternoon and early morning conditions, then either weighted equally (no day-length correction) or weighted proportionally to the hours of daylight (sunrise to sunset) and darkness for each day, to provide a day-length correction. For the computations in which day length varies, solar radiation intensity also varies.

3/ The moisture content that a fuel particle would attain if exposed for an infinite period in an environment of a specified constant temperature and humidity. When a fuel particle has reached its EMC, there is no net exchange of moisture between it and its environment.

Figures 4, 5, and 6 show the effect on the Energy Release Component for each of the three sample stations.

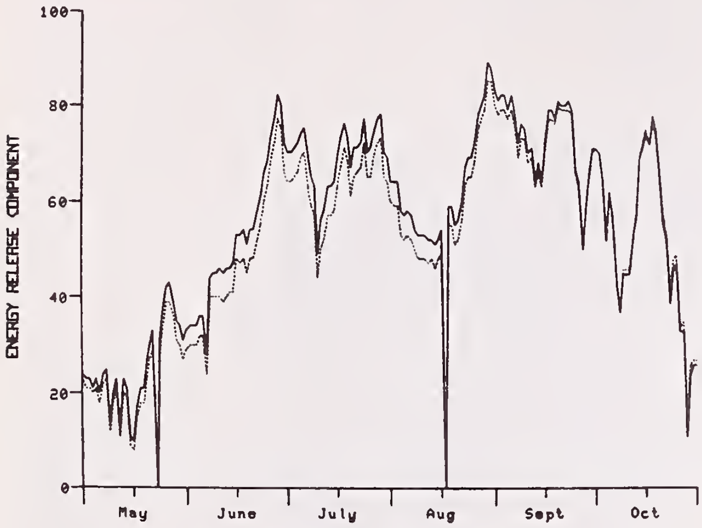

Figure 4.--Energy Release Component computed for Lytle Creek (1974 data) with a constant day-length value (dotted lines) and with variable day lengths (solid lines).

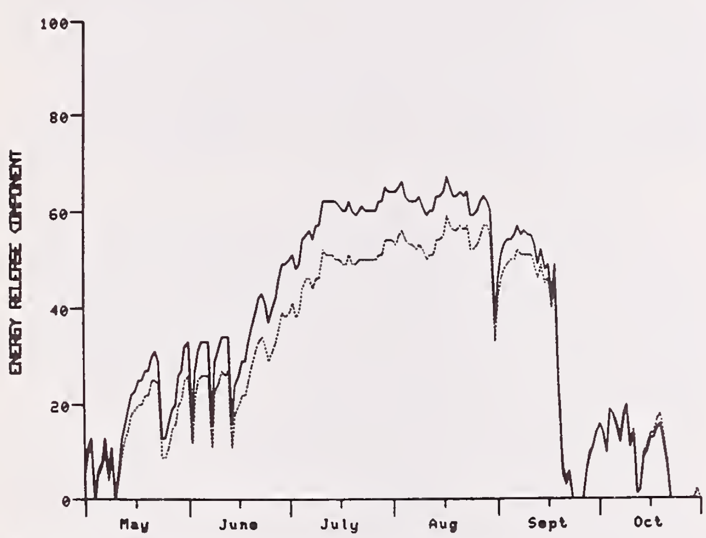

Figure 5.--Energy Release Component computed for Libby (1973 data) with a constant day-length value (dotted lines) and with variable day lengths (solid lines).

Due to the long summer day length in the northern latitudes, relative humidity recovery at night is much less than at more southerly latitudes. The daily weather data reflect this in that the EMC range calculated for Fairbanks (fig. 7) is much narrower than the EMC range calculated for either Lytle Creek or Libby (fig. 8 and 9). Burning conditions in Alaska often reflect this, with fires burning nearly as well at night as in the day.

Because the EMC range is so narrow in the northern latitudes, weighting the EMC by actual hours from daylight to dark does not result in Energy Release Component values that are much different from those obtained using an equal weighting of 12 hours of daylight to 12 hours of dark.

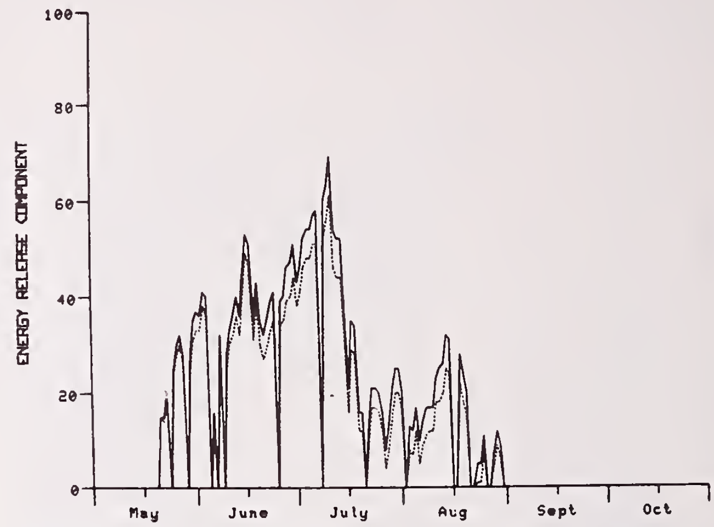

Figure 6.--Energy Release Component computed for Fairbanks (1975 data) with a constant day-length value (dotted lines) and with variable day lengths (solid lines).

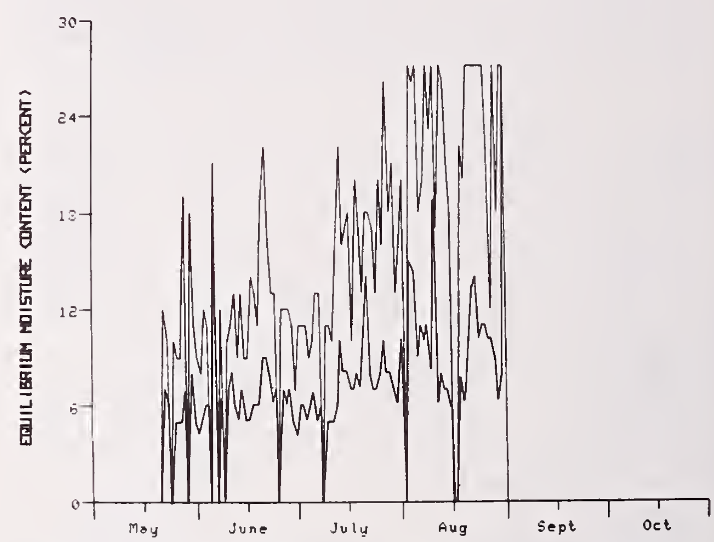

Figure 7.--Daily maximum and minimum equilibrium moisture content at Fairbanks (1975 data).

Figure 10 illustrates what the seasonal effect of day length would be on the Energy Release Component, if the weather data from Libby were assumed to have been observed at Fairbanks, (if the latitude of Libby were 65°). The large difference in the Energy Release Component, when computed with and without the appropriate day length correction for 65° latitude, occurs because the large day/night EMC range for Libby is combined with the large seasonal day length change at the latitude of Fairbanks.

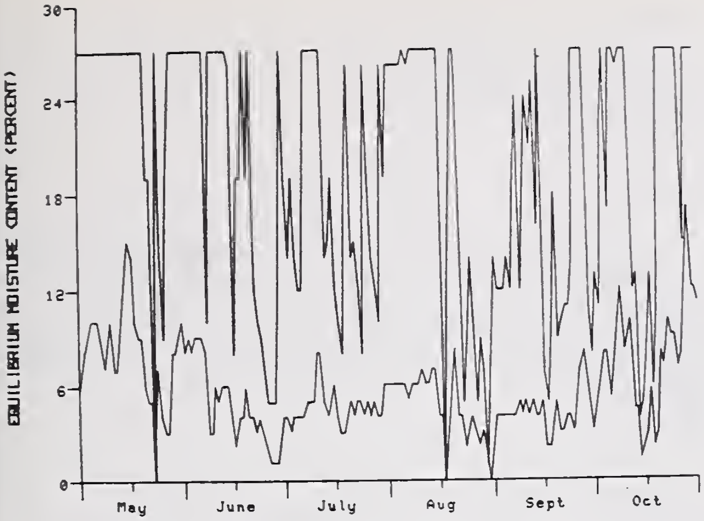

Figure 8.--Daily maximum and minimum equilibrium moisture content at Lytle Creek (1974 data).

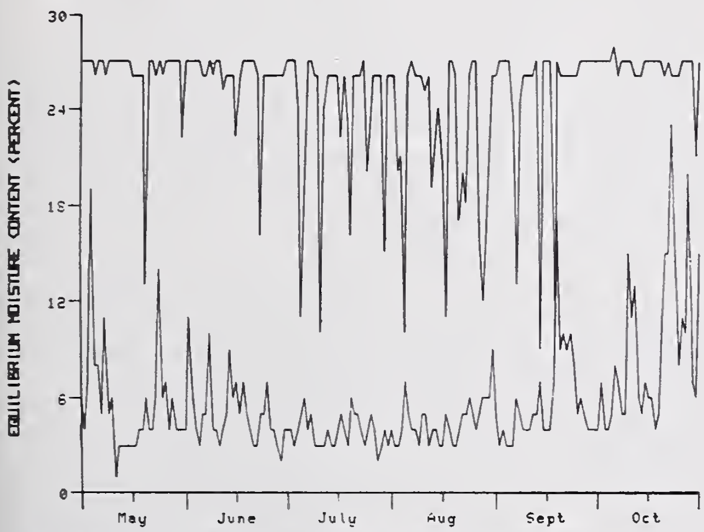

Figure 9.--Daily maximum and minimum equilibrium moisture content at Libby (1973 data).

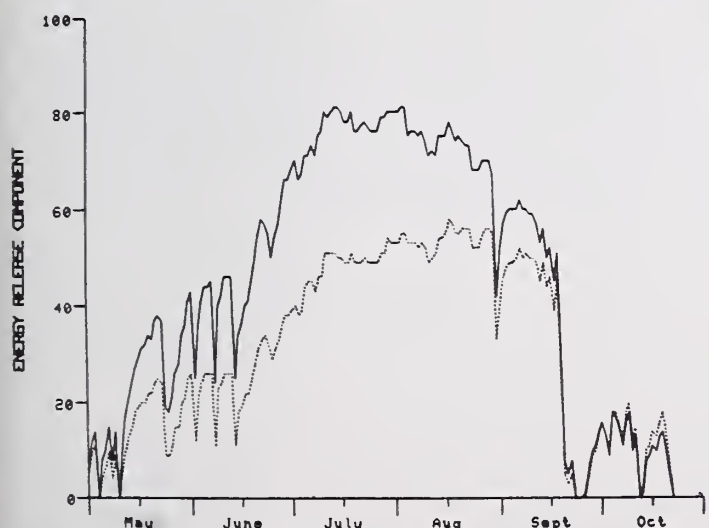

Figure 10.--Energy Release Component computed using 1973 weather data for Libby, with an assumed latitude of 65° with day-length correction (solid lines) and without the correction (dotted lines).

BURNING INDEX

The Burning Index is a normalized value of flame length, scaled to vary between 0 and 100. Figures 11, 12, and 13 show it is rather insensitive to seasonal changes in solar radiation intensity and day length. The reason for this lies in the parameters used to calculate the flame length--rate of spread, reaction intensity, and residence time.

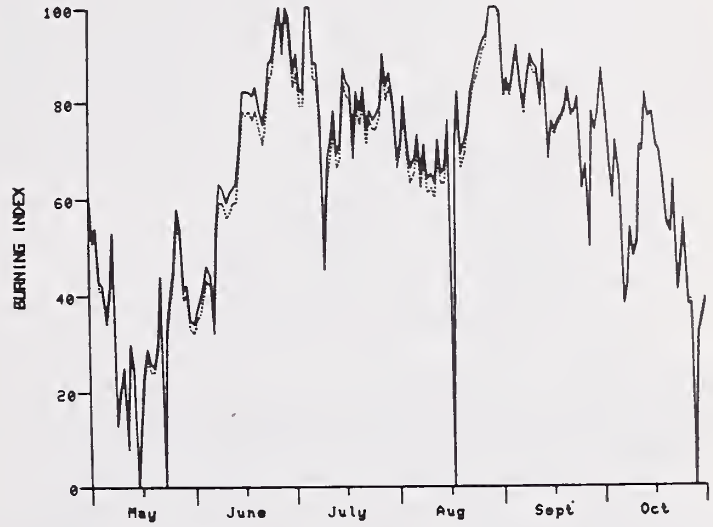

Figure 11.--Burning Index calculated for Lytle Creek (1974 data) with a constant solar radiation intensity and day-length value (dotted lines) and with variable solar radiation intensity and day-length values (solid lines).

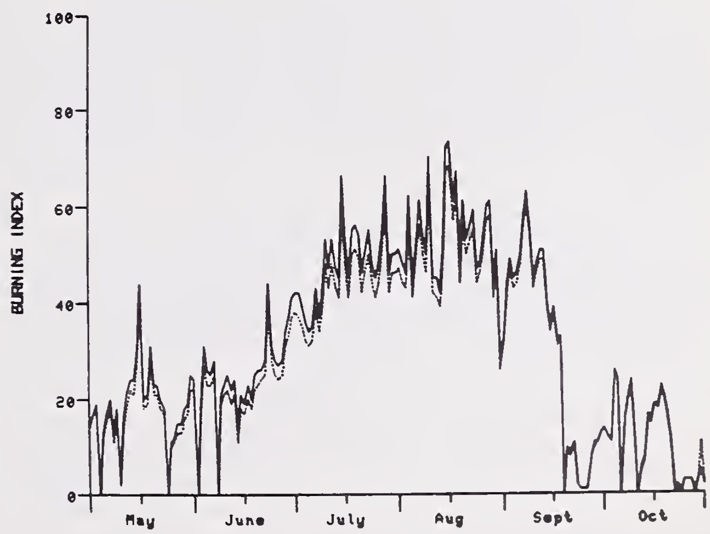

Figure 12.--Burning Index calculated for Libby (1973 data) with a constant solar radiation intensity and day-length value (dotted lines) and with variable solar radiation intensity and day-length values (solid lines).

The rate-of-spread is the unrounded value of the spread component. The reaction intensity (IRE) is an intermediate result developed in

the computation of the Energy Release Component (ERC = IRE/100). The residence time is dependent on the surface area/volume ratio, so it may be disregarded in this research.

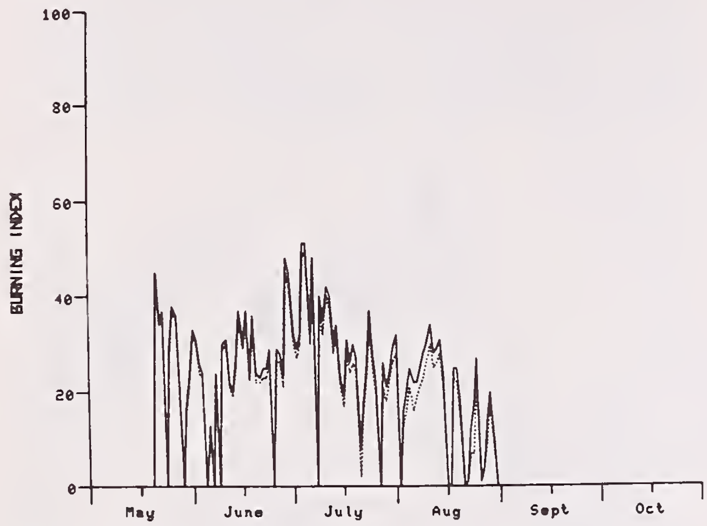

Figure 13.--Burning Index calculated for Fairbanks (1975 data) with a constant solar radiation intensity and day-length value (dotted lines) and with variable solar radiation intensity and day-length values (solid lines).

Thus, the seasonal effects of day length and solar radiation intensity on the Burning Index are expressed primarily through reaction intensity.

There is little seasonal effect in the rate-of-spread term because, for a given windspeed, it is primarily dependent upon the moisture content of fine fuels. The fine fuels, of course, have such a short timelag that even daily cycles have little effect on them.

So, the effect of correcting the Burning Index for seasonal changes of day length and solar radiation intensity is less than for the Energy Release Component, because the effect of the reaction intensity term in expressing seasonal cycles is diluted by rate-of-spread values in the Burning Index computation.

CONCLUSION

Seasonal changes in day length and solar radiation intensity at various latitudes influence the Man-Caused Ignition Component, the Energy Release Component, and the Burning Index in the 1977 National Fire-Danger Rating System.

Because the Energy Release Component is strongly influenced by large, dead fuels, seasonal effects are greatest in fuel models that have a heavy loading of 100- and 1,000-HRTL fuels. This is primarily because seasonal changes in day length affect the weighting of equilibrium moisture content (EMC) values calculated from early afternoon and early morning temperatures and relative humidities. The weighted EMC largely determines the moisture content of the heavier fuels during the fire season when relative humidity has more effect on these fuels than does precipitation duration.

The Man-Caused Ignition Component and Burning Index are less influenced by seasonal changes in day length and solar radiation intensity because they depend primarily on the moisture content of fine fuels. Because these fuels have such a short timelag (for example, 1 hour), their moisture is determined by the EMC at or near the basic early afternoon observation time. Thus, day length is of minor importance; however, the solar radiation intensity does produce a small effect through its influence on fuel temperature.

Because day length and solar radiation intensity have been shown to be important, appropriate calculations will be included in the computer program for the 1977 National Fire-Danger Rating System.

Development of a Fire Danger Rating System for Universal Application[1]

William E. Reifsnyder[2]/

Abstract.--At the request of the World Meteorological Organization, a hierarchical system for rating forest fire danger was developed. The system uses generally available meteorological measurements to evaluate the flammability of wildland fuels anywhere in the world. The basic framework is that of the US National Fire Danger Rating System. Key elements are adapted from that system and the Australian system.

INTRODUCTION

Fire is a natural part of many of the world's ecosystems. Indeed, many wildland ecosystems depend on fire for their regeneration and maintenance. But fire also, from man's point of view, exerts destructive influences on many ecosystems. Organic matter is consumed, trees are killed, soil is exposed to the erosive power of rainfall.

The delicate nature of the balance between man and the wildland environment is perhaps nowhere more evident than in the relationship between man, fire and the environment. Man often needs to use fire in manipulating the wildland ecosystem, but unwanted wildfire can destroy the values he has worked so hard to protect and develop.

Recognizing this, the United Nations Environment Program (UNEP) has undertaken several programs to further the understanding, use, and control of wildland fire for the protection of man's environment. In particular, UNEP asked WMO to prepare a report on forest fire danger rating systems and forest fire weather forecasting. I was asked by WMO to evaluate existing systems and to prepare, if possible, a system that could be used by developing countries or others recognizing a need for such a system.

RELATIONSHIP OF WEATHER AND CLIMATE TO WILDLAND FIRE BEHAVIOR

Given a complex of fuels in a wildland environment, the way that a fire develops and burns from an ignition source depends largely on meteorological and climate factors. The general structure of vegetation in an area is largely determined by the climate of the area, particularly such factors as temperature, precipitation and radiant energy input. The phenological development of plants in a vegetation complex depends in considerable measure on the seasonal progression of climatic elements.

Extended periods of low precipitation, low humidity, and high temperature produce conditions in which dead vegetation (and even to some extent living material) becomes highly flammable. Thus, in many regions, a well defined "fire season" is established.

The way that a particular fire burns in a complex of wildland fuels depends largely on meteorological conditions at that time, together with such other factors as topography and distribution of ignition sources. As early as 1913, forecasters of the U.S. Weather Bureau were authorized to issue fire weather warnings (Williams, 1916). These were primarily forecasts of impending dry and windy weather.

Development of specific information on the relationship between weather variables and fire behavior received great impetus from the work of Harry T. Gisborne in the United States and J. G. Wright in Canada during the decade of the 1920's (Gisborne, 1925; Wright, 1932). These men pioneered the development of systems for integrating weather variables into single index numbers that could be used to predict

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[1]/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, November 16-18, 1976.
[2]/ Yale School of Forestry and Environmental Studies, 360 Prospect Street, New Haven, CT, 06511.

the behavior of fires and the difficulty of controlling them. Their work in the development of forest fire danger ratings and "fire danger meters" formed the basis for much of the subsequent work that went on not only in North America but elsewhere in the world.

DISTRIBUTION OF FIRES AND FIRE WEATHER IN SPACE AND TIME

Fires can burn in wildland fuels anytime that antecedent and present weather have brought a sufficient quantity of fuel to a dry and flammable state. All that is needed is a source of ignition; this can be produced either by lightning or by man. Fires occur in nearly every vegetation type in the world with the possible exception of the tropical rain forest. Even here, however, fire is used in land clearing and shifting agriculture. Only a few forests in the world are so continuously wet that fires are virtually impossible.

The physical laws that control the behavior of wildland fires are the same everywhere on earth. It can be assumed, therefore, that it is feasible to develop a generalized system for predicting the behavior of fires in any vegetative complex subject to burning and to predict the weather variables that influence such behavior.

RELATIONSHIP TO FOREST AND WILDLAND MANAGEMENT

As a prerequisite for the development of a fire danger rating system, it is necessary to establish the uses to which such a system will be put. The level and intensity of wildland management will determine the interest in and need for the rating and predicting of fire danger. These management criteria will determine the nature of the system developed, its complexity and sophistication, the type and size of organization developed to implement the system, and so forth. The following non-exhaustive list of management criteria and activities is illustrative:

- (a) protection of life and property in wildland environments;
- (b) protection of the commercial value of the forest resource;
- (c) protection of watersheds from fire-accelerated erosion;
- (d) protection of high value plantations;
- (e) controlled use of fire for forest regeneration;
- (f) controlled use of fire for fuel reduction; and
- (g) use of fire in land clearing and vegetation-type conversion.

The first step in establishing a fire control plan must therefore be a statement and analysis of the fire-related management objectives. This in turn will imply the nature and level of fire-weather forecasting services required and the kind and complexity of fire danger rating system needed to further the objectives of the fire control plan. In terms of a fire danger rating system, possibilities range from a simple ignition index that will estimate the likelihood that fires can start and burn from natural or man-originated sources; to a multilevel system that will predict fire behavior, difficulty of control, manpower requirements, and so forth.

HIERARCHY OF FIRE DANGER RATING SYSTEMS

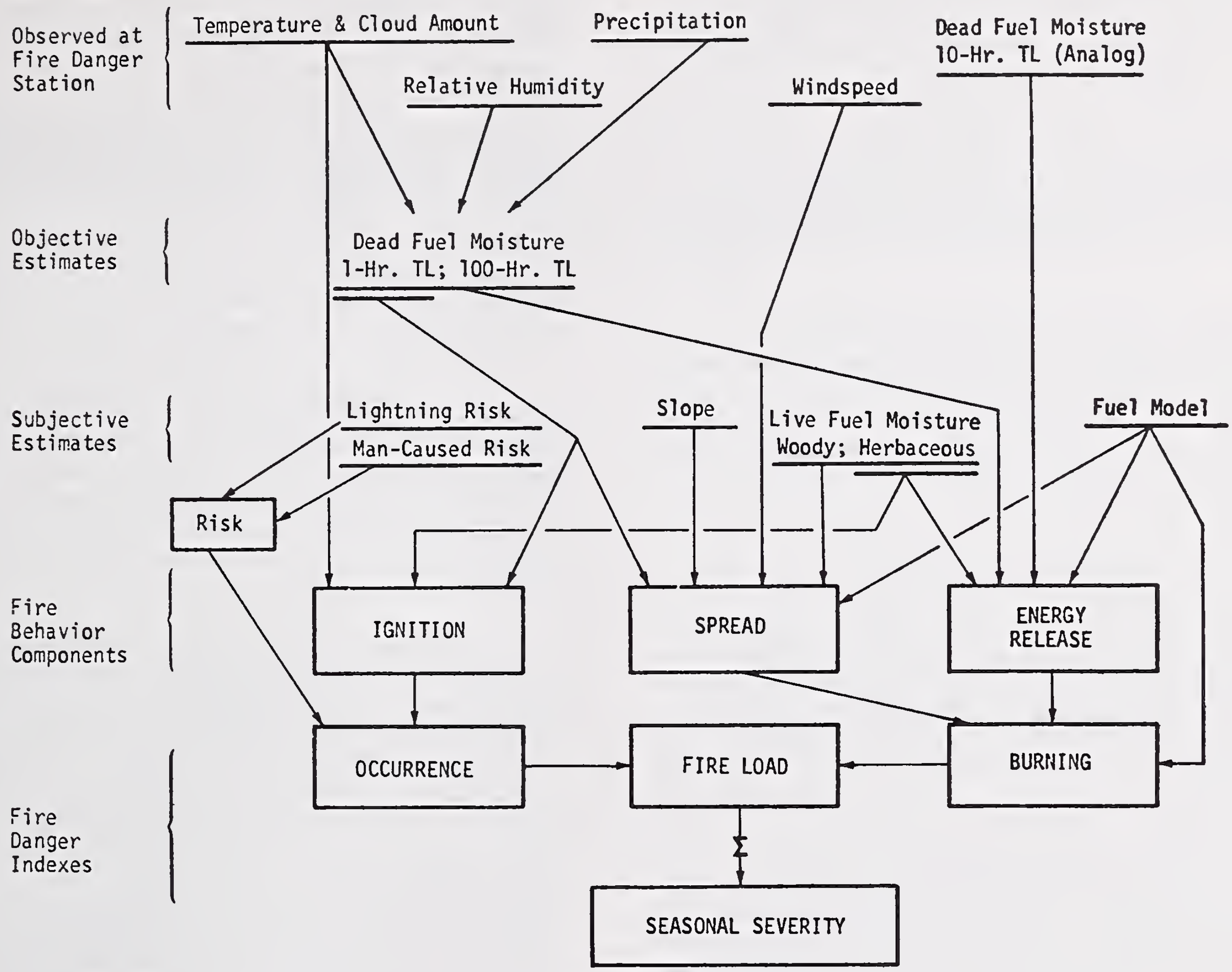
Discussion of the various levels of a fire danger rating system and the management uses to which the various components may be put is facilitated through examination of the structure of the U.S. National Fire Danger Rating System (Deeming and others, 1974). Although this was developed specifically for the U.S. system currently in use, it can be used as the basis for analyzing systems currently used elsewhere and can be used as the basis for the development of a system for universal application (fig. 1).

The meteorological elements that are inputs to this scheme relate either to the moisture content of various sizes of dead fuels[1] or to wind speed.

Level 1: Ignition. An ignition index indicates the ease with which fine fuels can be ignited from a simple ignition source such as a match, cigarette or lightning strike. It can be used by the forest manager as a measure of the likelihood that wildland fires would

[1] In this scheme, fuels are ordered according to their time rate of response to moisture changes. A one-hour timelag (TL) fuel is one that achieves 62% (1/e) of its equilibrium moisture content after a step change in ambient humidity. In the natural fuel complex, this represents fine fuels such as dry grass, individual conifer needles or hardwood leaves, small twigs, and the surface of the litter layer. Ten-hour timelag fuels include large twigs, branches with characteristic diameters of 1 to 3 centimeters and the surface litter layer of 2 centimeters depth. 100-hour timelag fuels include branch material from 3 to 8 centimeters in diameter and litter layers from two to 10 centimeters deep.

Figure 1. Structure of the U.S. National Fire Danger Rating System. (Deeming and others, 1974.)



start accidentally from the activities of man in wildland areas. From a meteorological point of view it is dependent primarily upon the moisture content and temperature of the fuel particle.

Level 2: Occurrence. The occurrence index is defined as a number related to the potential fire incidence within a specific area. It is related to the number of potential ignition sources within the area and to the ignition index. It gives the forest manager an indication of the relative number of fires that may occur in the rated area. It can be used, for example, as a guide to the level of detection services required.

Level 3: Spread Index. A spread index predicts the forward rate of spread of a fire in a particular fuel type on a particular slope when subjected to specific meteorological conditions. It can be used as a guide to estimate the time that deliberately set controlled fires will take to cover the area within a controlled burn. It can be used to estimate the speed with which control lines must be built in order to contain a fire.

Level 4: Energy Release. The energy release index, as its name implies, indicates the combustion rate and heat output in a given fuel type for a given complex of fuel moisture contents. It indicates how close to the fire edge fire control crews can work and thus may be used as a guide to effective attack methods.

Level 5: Burning Index. Burning index is defined as a number related to the contribution that fire behavior makes to the potential amount of effort needed to contain a fire in a particular fuel type within a rating area. It can thus be used to estimate the number of fire control personnel, kind and quantity of suppression equipment and so forth.

Level 6: Fire Load. The fire load index,

combining the burning index and the occurrence index, indicates the potential fire control job that may be faced by a forest manager in an area on a particular day. It provides an indication of the likely total fire suppression effort required on an area to meet the stated forest management objectives.

Level 7: Seasonal Severity. The seasonal severity index is a seasonal summation of fire load indices and is useful as an administrative tool for apportioning suppression forces and services among various units of a wildland area.

Obviously, not every forest fire control organization will need to utilize all of these indices. Developing organizations will start at a low level in the hierarchy and add components as their needs develop. Specific recommendations for such development follow.

GENERAL RECOMMENDATIONS

Development and utilization of a fire-danger rating system and a fire-weather forecasting system are essentially open-ended and can be pursued to any level appropriate to a particular nation's or region's needs, and to the quantity and quality of its cadre of technicians and scientists. For a nation with a small forestry department and perhaps a single weather forecasting center, the level of initial operations must necessarily be low. That is to say, the level of activity in rating and forecasting fire danger should be appropriate not only to the magnitude of the fire problem but also to the size and capabilities of the forestry and meteorological organizations.

CONSTRAINTS

In developing the specific recommendations contained in the next section, a number of assumptions and constraints were observed. The major ones follow.

The system should have universal application. Since fires everywhere burn subject to the same physical laws, it should be possible to develop a system that can be applied anywhere. Although this establishes the possibility of developing a universal system, the desirability rests on other grounds. First of all, the task of developing a separate system for each nation or for separate areas within each nation (as typified by the early development of fire-danger rating systems in the U.S.A.) is wasteful of scientific and technical talent. Development of separate systems would also delay the process in many areas where other tasks may have higher priority. Development of a single system for rating fire danger and fire climate will permit the intercomparison of fire hazards on a world-wide basis. This will permit rational studies of the allocation of fire research and fire-suppression efforts by national, regional, and United Nations agencies.

The system should be flexible and adaptable to a variety of administrative and governmental structures. The proposed system should not be keyed to the way any particular nation organizes its forestry and meteorological services. If possible, the meteorological parameters specified should be those that are normally produced by a forecast center.

The proposed system should be simple and easy to apply. There is an obvious need for simplicity in formulating and using the fire-danger rating system. Obviously, a system can be as complicated as needed; but at the start it should be easily usable and understandable by field personnel. Otherwise, it simply will not be used.

The system should be hierarchical in nature. As implied earlier, various fire control organizations will need systems of different levels of sophistication. The proposed system should permit an orderly and logical transition from one hierarchical level to another. Each level should represent something added to the level below, rather than something substituted for it and replacing it. Some substitution may of course be necessary as scientific understanding of the meteorological influences on fire behavior increases. But if the underlying hierarchical structure is sound, such substitutions can be made with minimal disruption to the operation of the system.

DEVELOPMENT OF AN IGNITION INDEX

The single most important wildland fire danger index for a nation that is developing a wildland fire management system is an index that will indicate the likelihood that a wildland fire will start given a source of ignition such as a cigarette, debris fire or a lightning strike. Wildland fires normally start in fine dead fuels such as dry grass or leaf litter. The drier the fuels, the more likely an ignition source will start a fire. The moisture content of the fine dead fuels depends on the temperature of the fuel particle and on the relative humidity of the air immediately in contact with it. Fine dead fuels respond very quickly to changes in ambient temperature and humidity conditions. However, if the grass and herbaceous vegetation is only partially cured, the effective moisture content of the fine fuels is raised

because of the high moisture content of the green living material.

One existing rating system, the US National Fire Danger Rating System (NFDRS), includes a component that estimates the moisture content of fine fuels less than 7 millimeters in diameter. (These are the so-called one-hour timelag fuels indicated on figure 1.) Because equilibrium moisture content of a fine fuel depends on whether the fuel particle is undergoing a drying or wetting phase, an assumption must be made as to the regime to which the particle is being subjected. The NFDRS assumes a drying phase inasmuch as high fire danger normally occurs in the afternoon after the fuels have been drying from a morning moist condition (Fosberg and Deeming, 1971). Although a specific drying regime was utilized in the preparation of the tables, that appropriate to a continental climate, it is likely that the system will work reasonably well anywhere, certainly as a first approximation. The meteorological elements required for the estimate of the ignition index are air temperature and relative humidity measured in a standard weather shelter and the state of the weather (whether sunny or cloudy). Thus, calculations can be made based on standard meteorological observations. The time of observation should be close to noon.

DEVELOPMENT OF RATE-OF-SPREAD INDEX

The rate of spread of a fire in a given fuel complex depends on wind speed and slope in addition to fuel moisture content. Also, the moisture content of heavier fuels influences the intensity of a fire as well as its forward spread. These are fundamental fire behavior parameters that are important not only to the control of wild fires but also to the behavior of fires set for management purposes. For these purposes, it is desirable that the danger rating be interpretable directly in terms of forward spread of fire.

The Australian system (McArthur, 1967) fits these criteria. It was developed for eucalypt forests in Australia and has been applied successfully in the subtropical climates in Australia and in eucalypt and pine plantations in Zambia (FAO, 1971). It should be noted that the McArthur system is based on more than one thousand experimental fires, permitting direct interpretation in terms of rate of spread.

The system can be described briefly as follows. The system uses standard meteorological measurements of temperature, relative humidity, dewpoint, wind speed, and rainfall as basic input parameters. Fine-fuel moisture is determined implicitly through the measurement of temperature and relative humidity. Moisture content of medium and heavy fuels is kept track of through a bookkeeping system utilizing rainfall amount, days since rain, and maximum air temperature. Wind speed is included as a major influence on rate of spread and rate of combustion.

The resultant index number can be interpreted in terms of rate of forward spread and flame height for various quantities of fine dead fuel ranging from five to 25 tonnes per hectare.

It should be noted that the US NFDRS has the capability of evaluating a danger rating for an essentially infinite variety of fuel types in which fuel amounts are distributed among fine, medium and heavy fuels. At present, the system has been adapted to eight different fuel types (called fuel models) representing typical fuels found in the United States. Development of this system should be monitored for possible application in other regions inasmuch as it appears to be highly adaptable to any fuel complex and any climatic regime. In its present form, it may be difficult for a forestry organization unfamiliar with fire danger rating systems to implement it because of its relative complexity.

IMPLEMENTATION

The Food and Agriculture Organization of the United Nations has under advisement the establishment of several regional fire weather forecasting and research centers. These have been proposed for the Mediterranean region, Africa and Central America. When and if these centers are established, the proposed fire danger rating system will be implemented on a trial basis. This should provide a valid test of validity for use in other regions of the world.

ACKNOWLEDGEMENT

The developments reported in this paper were accomplished while the author was employed as a consultant to the World Meteorological Organization. A more complete account, including proposals for fire weather forecasting systems, will be published as a WMO Technical Note.

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Session IV

Atmospheric Aspects of Forest Insect and Disease Control

Chairman: Keith Shea

U.S. Department of Agriculture

Washington, D.C.

Airflow in the Forest Canopy — A Review of Current Research on Modeling the Momentum Balance[1,2,3]

James D. Bergen[4]

Abstract.--There is currently no generally accepted model for the momentum balance of air flow in a forest canopy. The defects in existing models are fundamental. They reflect basically a lack of information on the flow near highly porous, bluff, and irregular bodies at appreciable speeds, as well as conceptual difficulties in superimposing turbulence fields of differing macroscales and random secondary flow patterns.

Three recent models for wind flow in a forest canopy (developed by Cionco et al, Barr, and Bergen) are examined as divergent solutions to the problems of the vertical velocity profile in an extensive forest stand. The models are typical of three main approaches to the problem of estimating the vertical shear stress terms for the time- and space-averaged momentum balance through the canopy layer.

In the first, the vertical momentum transport is attributed entirely to local turbulence, and the eddy viscosity is related to the average local speed and the foliage drag by equating the dissipation of kinetic energy by the foliage drag to the work done by the mean flow via the vertical turbulent shear stress.

In the second solution, an effective viscosity is assumed to depend on local speed and a length scale determined by the total canopy density, the tree height, and the distance to the forest floor. The relation is determined such that it interpolates between very high densities and a vanishing density.

The last model attempts to evaluate the apparent viscosity empirically as a function of foliage distribution and local speed. The vertical shear stress is assumed due to a super position of (1) turbulent motions due to foliage wakes and those due to large-scale vertical shear, and (2) small scale secondary circulations.

None of these models correctly predicts the velocity and/or speed maximum found in the subcanopy space in field and wind tunnel investigations. The trend in opinion on this important difficulty in all current models is that local circulations occur in a typical forest stand which are of the same vertical scale as the canopy. Transport due to these motions cannot be parameterized in the same fshion for the space and time averages necessary to ensure continuity between the heteorogeneous canopy layer and upper homogeneous region as is the case for smaller scales of motion. Therefore, an extra term of a relatively complex nature appears in the momentum balance.

1/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, Nov. 16-18, 1976.

2/ Research funded in part by the USDA-expanded Douglas-fir Tussock Moth Research and Development Program, P.O. Box 3041, Portland, Oregon.

3/ Because of the length of this paper, it will be issued at a later date as a Rocky Mountain Forest and Range Experiment Station publication.

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Atmospheric Transport of Insects and Disease[1,2]

Robert L. Edmonds[3]

Abstract. Airborne insects and diseases cause considerable damage to forest ecosystems. The meteorological factors influencing the production, release, dispersion, deposition and viability of airborne insects and fungus spores are examined. The potential for disease spread is examined over both long and short distances. Modeling as a tool for integrating data, predicting spread and use in control is discussed.

INTRODUCTION

The major concern with damaging forest insects and diseases lies in their ability to spread. If they didn't spread and occupy new space, there would be little need for concern.

Airborne dispersal is the most rapid mechanism for the spread of insects and diseases and most dangerous forest pests are spread in this way. This spread is influenced by meteorological conditions, and it is this influence on the production, release, viability, dispersion and deposition of insects and fungus spores which are examined here. Questions involving how far airborne forest insects and diseases are capable of spreading, the prediction of spread, and the use of systems analysis as a tool for control are also discussed.

THE IMPACT OF AIRBORNE DISEASES AND INSECTS

Our major interest in understanding and controlling forest pests results from the damage they do to timber resources. Economic damage to forests by airborne insects and diseases is considerable and annual growth losses and mortality amount to millions of dollars (Davidson and Prentice 1967).

[1]/ Paper presented at the 4th National Conference on Fire and Forest Meteorology, St. Louis, Nov. 16-18, 1976.

[2]/ Partial support for this work was provided by the USDA Douglas-fir Tussock Moth Program, Portland, Oregon.

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Several examples illustrate this point. The gypsy moth (Porthetria dispar) had defoliated thousands of hectares of hardwoods in the northeastern United States since its introduction in the 1890's. In 1973, defoliation occurred on 728,450 ha (U.S. Forest Service 1975). Similar destructive defoliation is caused by the Douglas-fir tussock moth (Orygia pseudotsugata) in the western United States. Nearly 324,000 ha of Douglas-fir and true firs in Oregon, Washington and Idaho sustained some degree of defoliation (U.S. Forest Service 1975). The spruce budworm (Choristoneura fumiferana), the most widely distributed destructive insect in North America, has killed many trees in the last 150 years and 2.5 million ha were affected in 1973 in the east (U.S. Forest Service 1975).

Airborne forest diseases, which are mostly caused by fungi, are generally not as dramatically evident as insect outbreaks, but they do cause considerable economic damage. The annual loss to white pine blister rust caused by Cronartium ribicola has been estimated at approximately 9.6 million m^3 of lumber (Davidson and Prentice 1967). The disease generally makes the growing of nonresistant white pine an unprofitable venture.

Fomes annosus root rot has been a serious problem in Europe for more than 100 years, particularly in thinned plantations where airborne spores infect exposed stumps. This root rot has emerged as a problem in intensively managed conifer stands in the United States and annual mortality in the southeast is estimated to be 192,500 m^3 (Davidson and Prentice 1967). Fusiform rust caused by Cronartium fusiforme is a limiting factor in the successful management of loblolly and slash pines in the southern United States.

In the Lakes States region hypoxylon canker (Hypoxylon pruinatum) is estimated to cause an

annual growth loss in aspen of 5.4 million m^3, which is equivalent to about 31% of the net growth of aspen types in the survey area.

There are many more examples of the impact of airborne insects and diseases which could be listed, but the above examples serve well to illustrate the loss of fiber which occurs each year due to these agents which otherwise would be available for use.

PROPERTIES OF AIRBORNE FUNGUS SPORES AND INSECTS

Airborne fungus spores and insects differ considerably with respect to size, shape, terminal velocity, viability and metabolic state. Insects generally become airborne in an actively metabolizing state and many insects are not well adapted for aerial dispersal. Fungi are generally dispersed in the form of spores (either sexual or asexual) which are hardier, metabolically less active, and often better adapted to aerial dispersal (Gregory 1973). Hyphael fragments may also be airborne. The above properties, in combination with meteorological conditions, largely determine the distance of spread of airborne insects and diseases.

Properties of Spores

Spores may be unicellular or possess a few cells with an outer cell wall surrounding the nuclear material. The spore walls may be very thick in some species. The surface may be hydrophobic or hydrophilic, sticky, smooth or spiny. Spores may be transparent and colorless (hyaline) or colored, with yellows, reds, browns and purples being the most common. Although most spores are dispersed as a single unit aggregates do occur.

Generally specific gravities of spores fall between 1.1 and 1.2, although lower and higher values do occur. Spore sizes and shapes are variable. Small spores tend to be spherical, whereas larger spores may be extremely elongated. Spore diameters range from less than 5 μm to as much as 115 x 350 μm for some ascospores. Most spores are 5 - 50 μm in diameter.

Spore surfaces may also be electrically charged, either positive or negative. The size, shape, density, surface roughness and electrostatic charge control the aerodynamic behavior of the spore, particularly the terminal velocity.

Fungus spores are subjected to gravity fall at a terminal velocity governed by Stoke's law, which in simplified form states that the rate of fall per second of a spherical spore is proportional to the square of its radius. Table 1 shows the dimensions and terminal velocities of some common spores. Spores of Fomes annosus, for example, are well adapted for aerial dispersal, because of their small size, although larger spores such as wheat rust (Puccinia graminis tritici) urediospores are capable of traveling long distances. Spore size thus does not entirely determine travel distance. When turbulence is high, say during the day, differences in terminal velocities are minimized. Many larger spores are also elongated and the terminal velocity of such spores is less than that of spherical spores of the same volume.

Viability ultimately determines the effective spread of spores since they must arrive in a living state to cause disease. The airborne phase can be regarded as a retarded decay process, and death of the cells is sometimes

Table 1. Terminal velocities and dimensions of representative spores.

Genus or species	Spore type	Dimensions (μm)	Terminal velocity cm sec^{-1}
Alternaria sp.	conidia	20 x 10	0.3
Cladosporium sp.	conidia	10-14 x 3.8-5.2	0.07
Cronartium ribicola	urediospore	22 x 19	0.8
Fomes annosus	basidiospore	4.5 x 3.5-4.5	0.07
Puccinia graminis tritici	urediospore	30 x 18	1.06

rapid (Gregory 1973). Humidity, temperature and radiation are the three factors known to greatly influence viability.

The hazard of dessication is greatest in the daytime and in air layers near the ground. At higher altitudes, and at night, conditions are more favorable. Temperatures in the upper atmosphere may in fact be preservative rather than lethal.

The wavelengths of radiation which are most lethal are in the ultraviolet (UV) region. Ascent to the upper air greatly increases the UV dosage except in clouds. Pigmented spores have more protection than hyaline ones. There is also some evidence of the lethal action of radiation in the visible region (Gregory, 1973). Photoreactivation may reduce apparent radiation damage as spores return to lower altitudes. Interactions of temperature, moisture and radiation are not well understood, but Carlisle (1970) has shown that low temperatures and dessication may protect spores against radiation damage.

The impact of air pollutants on spore viability is also not well understood, but it is thought to vary with atmospheric conditions. Lighthart (1973), for example, found that high humidities protected airborne bacteria from loss of viability due to carbon monoxide exposure. Viability varies greatly among the classes of airborne fungi. Kramer and Pady (1968) found Fungi Imperfecti with dark thick spore walls had the highest average germination (80%), while lighter colored Fungi Imperfecti such as Cladosporium sp. had lower rates of germination (45%). Basidiospores were considerably lower at 6%. Rust urediospores had 32% germination. Many common forest pathogens are basidiomycetes with hyaline spores.

Some spores have a very short life span in the atmosphere. Cronartium ribicola basidiospores are given a "half-life" of only 5 hours (Yarwood and Sylvester 1959). Other spores have considerably longer life spans. Pady and Kapica (1953) found some spores alive in Arctic air masses originating far to the south.

Properties of Insects

The size and shape of airborne insects is generally quite different from fungus spores. Insects are measured in terms of millimeters rather than micrometers and tend to be elongated. As mentioned previously one of the factors that determines the distance a particle is dispersed in the atmosphere is the terminal velocity. Table 2 shows terminal velocities for various sizes of Douglas-fir tussock moth larvae with and without silk.

Table 2. Terminal velocity of Douglas-fir tussock larvae as functions of length, weight and silk length.

Larval length (cm)	Silk length (cm)	Larval weight (mg)	Terminal velocity (m sec^{-1})
0.3*	90	-	0.252
	60	-	0.328
	30	-	0.467
	20	-	0.544
	10	-	0.651
	0	-	0.812
0.318**	0	0.65	1.906
0.635**	0	1.00	2.103
0.794**	0	1.10	2.790
1.100**	0	7.10	2.900

* First instar. Data provided by R. Mitchell, U.S. Forest Service, Corvallis, OR

** Other Instars.

Terminal velocities for these soft bodied larvae are several orders of magnitude greater than those for the fungus spores listed in Table 1, perhaps indicating that insects are not as well adapted for long distance dispersal as fungus spores. Despite their relatively huge size many first instar larvae have several features which enable them to remain airborne longer than would be anticipated. Douglas-fir tussock moth larvae, for example, are covered with a layer of hairs which increases buoyancy. This is supplemented by the silk which trails behind. Table 2 indicates that the terminal velocity of a larva with 90 cm of silk is approximately one third of that with no silk. The elongated shape of the larvae also reduced the terminal velocity. However, larger larvae in later instars have extremely large settling velocities and are poorly adapted for airborne dispersal. Similar relationships were determined by McManus (1973a) for gypsy moth larvae.

Aphids have somewhat similar aerodynamic properties to the larvae discussed above, but lack trailing silk. If insects are much larger than several millimeters in lenth, they generally need flying power to disperse.

Viability also determines the ultimate effective spread of airborne insects. Wellington (1945) concluded that temperature was the limiting factor in insect survival. Any flying insect cooled below the threshhold temperature for flight folds its wings and falls in a trajectory dependent on terminal velocity and wind components. Soft bodied insects such as aphids are soon killed by 0°C temperatures, but other insects can withstand freezing and thawing. Soft bodied insects are also more prone to dessication.

RELEASE OF SPORES AND INSECTS INTO THE ATMOSPHERE

Spore Release

The primary functions of spores are dispersal and survival of a species. There are two strategies of spore production in the fungi. Some species produce large numbers of small spores that facilitate dispersal, but are not well adapted for survival. Other species produce fewer larger spores better adapted for survival.

Spores are either actively or passively discharged (Ingold 1965). Active dispersal involves either turgid living cells or drying and commonly ascomycetes and basidiomycetes employ these methods. With passive dispersal either slime-spore or dry-spore discharge occurs and this method is employed largely by Fungi Imperfecti. Rain and wind are the most common triggering mechanisms. It might be expected that many of the fungal propagules in the air would be associated with dust particles. However, this does not appear to be so and most spores appear to be directly liberated into the atmosphere.

Spore release commonly follows circadian patterns determined by one of the major environmental factors which also show rhythms of this kind, e.g., light, temperature, relative humidity and wind velocity. For some spores the maximum release is at night or in the early morning before dawn, or shortly after sunrise (ascomycetes and basidiomycetes). Other spores have a maximum early in the afternoon, particularly colored thick walled spores exhibiting passive release (Fungi Imperfecti). Normally one of these seems to dominate. In a number of ascomycetes light induction or inhibition is dominant with light affecting the last stages of maturation.

Early afternoon and predawn maxima in spore release is generally related to temperature and relative humidity. Wood (1966) found a maximum release of basidiospores of Fomes annosus around midnight and a minimum around noon. Basidiospores of Cronartium fusiforme show a similar pattern with spores being produced at night and early morning. Occurrence is closely related to the number of hours exceeding 97% relative humidity (Snow and Froelich 1968). Cronartium ribicola is also similar.

How many spores are produced by a single fruiting body? Ganoderma applanatum, a common wood rotting organism may produce 3×10^{10} spores in a single day and a 2.5 cm diameter colony of Penicillium may produce as many as 4×10^8 conidia day^{-1} (Ingold 1946). Environmental conditions, particularly moisture and temperature, influence the length of time a fruiting body sustains production. In the polypore fungi many species are woody and perennial and are able to continue sporulating throughout the year as long as moisture and temperature conditions are suitable.

With Fomes annosus (a polypore fungus) some spores are produced in most seasons of the year except during periods of extreme drought or cold in Europe, Canada and the northern United States. Maximum production occurs in late summer or fall. In the southeastern United States, greatest spore production occurs during fall, winter and spring. Few, if any, are produced in summer (Hodges 1969).

To become airborne spores must pass through the laminar boundary layer surrounding the fruiting body. During calm periods at night this layer is very thick, but it may be reduced to <1mm with high winds. Once free of this boundary layer, spores are dispersed in the wind field

Insect Release

There are two major insect forms dispersed in the atmosphere; (1) non-winged forms including immature insects, such as Lepidopterous larvae, and wingless adults, such as aphids and (2) winged forms.

The non-winged forms are more analagous to fungus spores since they are under many of the same environmental influences, particularly the effect of gravity. Small winged forms, although having the ability to fly,sometimes maintain positions where they do not use their flying power and are passively dispersed. Leaf hoppers behave in this manner.

The actual movement of the insect into the air is usually directly influenced by microclimate. Temperature probably has the greatest influence on the activity of arthropods. Wellington (1945) found that the minimum temperature (threshold) for flight initiation in three species of Homoptera was about 14°C, with the bean aphid having a threshold temperature of

13-15°C.

With winged insects temperature may limit activity for short periods but it generally does not prevent dispersion. However, with passively blown forms temperature may limit predispersal behavior and greatly inhibit dispersal. Gypsy moth larvae, for example, after hatching in spring, climb to dispersal sites in the tree tops in response to light. McManus (personal communication), however, indicated that dispersal did not occur when a cyclonic disturbance dominated for three days resulting in temperatures below the threshold of activity for the larvae. Similar behavior is exhibited by tussock moth larvae. Larvae observed by the author did not climb unless temperatures were above a threshold of 11-13°C. In general, humidity is not thought to be a limiting factor in dispersion. Activity is greatest at lower relative humidities.

High velocity winds are inhibiting to insect release; very slight breezes appear to stimulate both the flight behavior of winged forms and the dispersive behavior of passively carried insects. McManus (1973a) found that gypsy moth larvae will actively drop when winds are less than 8 km hr^{-1}, but adhere when winds are higher. Jensen and Wallin (1965) indicate that aphid take off was delayed by 4-10 hours by winds of 4-8 km hr^{-1} and delayed 24 hours by winds of 8 km hr^{-1}. This phenomena is common in the Orders Diptera, Thysanoptera, Hemiptera and Homoptera.

Most insects tend to take off when winds are suitable for dispersal, which generally for passively dispersed insects, tends to be at a maximum in the early afternoon. Many adult insects including the spruce budworm, however, are released at night.

Although crowding has been frequently mentioned as a stimulus to dispersal, there is a large body of evidence to the contrary (McManus, personal communication). The locust phase of many grasshoppers, however, is induced by increased densities in their permanent breeding ground. Generally, it can be concluded that many adult insects are released at night while most larval and immature insects are released during the day. On a seasonal basis most activity is in spring, summer and fall.

DISPERSAL AND DEPOSITION PROCESSES, AND ATMOSPHERIC CONCENTRATIONS OF SPORES AND INSECTS

Dispersal Processes

The processes determining release into the atmosphere of fungus spores and insects have been described. What is the fate of these particles once they are released into the atmosphere? They are dispersed downwind vertically and horizontally as a result of atmosphere turbulence. Turbulence can be either mechanical or thermal in origin. Atmosphere stability also markedly affects dispersion with greatest dispersion under unstable conditions and least under stable conditions. Three scales of atmospheric transport are recognized; micro-scale, meso-scale and large-scale. Each possesses definite time and space scales.

Micro-scale transport is limited to small time scales (< 1 hour) and space scales varying from centimeters to a few hundred metres (short distance dispersal). For meso-scale transport, the appropriate time and space scales are days and a few hundred kilometers or less. Large-scale transport encompasses global circulation patterns and very long time scales. The last two classes are considered long distance dispersal.

Deposition Processes

The principal methods of spore and insect deposition in nature are sedimentation, impaction, turbulent deposition, rain washing and electrostatic deposition.

Sedimentation. In turbulent air above ground, the effects of gravity on spore deposition are slight except perhaps under stable conditions on clear nights when the laminar boundary layer may extend several meters. Wind tunnel experiments confirm that the effect of sedimentation is slight at wind speeds exceeding 2 m sec^{-1} (Gregory 1973). Wind speeds beneath a forest canopy are generally less than 1 m sec^{-1} and in such cases sedimentation may be important. Sedimentation is more important for insects because of their larger size.

Impaction. Impaction is inefficient when small spores approach large obstructions at low speeds. Conversely, impaction is more efficient when large spores are blown towards small objects at high wind speeds. Large spores would thus seem to have an advantage with respect to impaction on foliage. Dry-spored airborne leaf pathogens usually have large spores while soil inhabitants are characterized by small spores unsuitable for impaction.

The larger size of insects would also favor impaction on foliage. Many forest defoliators such as the Douglas-fir tussock moth also trail silk which aids in the impaction process.

Turbulent Deposition. Spores in air flowing over horizontal surfaces will be deposited

at rates greater than those calculated for sedimentation alone. Rishbeth (1959), for example, found that spores of Fomes annosus were even deposited on the undersurface of pine discs exposed a few meters above the ground. These patterns result from turbulent deposition. Turbulent deposition also occurs at larger scales as a result of terrain irregularities and frontal activity.

Rain Washing. The optimum size for deposition in rain varies with the size of prevalent raindrops. Rain washing of air rapidly ends the dispersion process, and it is more effective for larger spores. Snow is unimportant, but large numbers of microorganisms have been found in hail stones. The small spores of Fomes annosus are generally not removed from the atmosphere by rain except where frontal activity occurs.

Rain itself is probably not efficient in removing insects from the atmosphere, but insects are commonly brought to the ground in down drafts associated with frontal activity associated with rain.

Electrostatic Deposition. The charges observed on basidiospores and ascospores are presumably acquired in the liberation process. This charge in very small particles such as bacteria could affect the terminal velocity, but in larger fungus spores the effect is less and the initial charge could well be masked by the capture of ions in the atmosphere. Electrostatic deposition is unlikely to be of importance with insects.

The Relative Importance of Deposition Mechanisms. The relative importance of the various deposition processes differs in different positions. Close to the source impaction may dominate except in calm air where sedimentation plays a major role. Rain washing will have a greater effect at longer distances from the source.

Local irregularities in terrain and tree canopies cause turbulence resulting in updrafts and sowndrafts. This may alter the deposition patterns in an area. Turbulent deposition may occur on the lee side of hills and this may explain why gypsy moth and tussock moth infestations are commonly observed on hill tops rather than in valleys.

Levels of Fungi and Insects Found in the Atmosphere

The Background Air Spora Near the Ground

Gregory and Hirst (1957) in a mixed agricultural environment determined that the mean spore concentration at 2 m from June to October 1952, was 12,500 m^{-3}. The commonest spore type was Cladosporium sp. (accounting for 47%). Basidiospores are not efficiently caught by surface traps and they may be more important than indicated.

It has already been demonstrated that spores and insects are released into the atmosphere in certain rythms. This rhythmic variation in spore liberation clearly contributes to airborne concentration. However, if the numbers liberated per hour remained constant, concentration would still tend to be greatest at night because of slower wind speeds, decreased turbulence, absence of convection and tempperature inversions. Most spores also show a seasonal periodicity with highest numbers in late spring, summer and fall.

Measurement of the upper air spora was first attempted from towers and tall buildings and later from balloons and aircraft. One would expect a decreasing population with height but this rarely seems to be the case and commonly profiles may increase or be similar up to 1500 m. This is perhaps due to the fact that the thickness of the turbulent zone fluctuates and the vertical concentrations are continually building up or decaying. There is some evidence of a "biological zone" occurring at middle heights, which can probably be explained in terms of temperature inversions, air masses and precipitation (Gregory 1973).

Levels of Insects in the Atmosphere

Although studies of airborne insects have been conducted in recent years, no study as extensive as that recorded by Glick (1942) has been repeated. During 5 years from 1926 to 1931, The USDA in Louisiana sampled 28,739 specimens taken from 6 m above the ground to as high as 5,000 m. The concentrations of total insects at 305 m varied from $3.6 \times 10^{-6} m^{-3}$ at night to $3.0 \times 10^{-6} m^{-3}$ during the day. Concentration at 6 m was $1.4 \times 10^{-5} m^{-3}$. There are wide differences in concentration of insect groups during the day and night. For example, Hymenoptera are far more numerous in the daytime than at night.

Of all insects taken, Diptera were the most abundant and the number decreased with height. At times, however, there may be wide deviations from the expected average population gradient in the upper air. Insects often emerge in great numbers. Butterflies and grasshoppers, flying on their migration or invasion routes will at times fill the air. The author has sampled Douglas-fir tussock moth larvae at a concentration of 0.09 m^{-3} close to the source. These concentrations, however, are still much smaller than even average spore concentrations

Short Distance Dispersal and Deposition in the Forest

Most experiments to determine the distance that fungus spores travel have been conducted over relatively flat terrain (Gregory 1973). Very few studies involving fungus spore or insect dispersal have been conducted in forests. Dispersion beneath the forest canopy may markedly differ from what one expects above the canopy under the same ambient conditions. Below canopy dispersion is particularly important in the case of fungal spore dispersion since many of the spores are released at or near the forest floor.

Van Arsdel (1967) in a paper on the nocturnal diffusion and transport of spores indicated that spores released at night play an important role in the spread of some major forest diseases. Fomes annosus, Cronartium ribicola and Cronartium fusiforme all release hyaline basidiospores at night. Understanding dispersion patterns in and above the forest at night and the expected distance of travel is thus important in understanding the spread of disease.

Edmonds and Driver (1974) and Fritschen and Edmonds (1976) examined dispersion of spores of Fomes annosus and similarly behaving fluorescent particles under a variety of meteorological conditions in a Douglas-fir forest. Basidiospores released near the ground at night under cold air drainage conditions with wind speeds of < 0.5 m sec^{-1} are capable of traveling at least 240 m before settling out, but dispersion patterns are complicated by shifting wind fields and traditional statistical dispersion theories do not apply. Deposition patterns are even more complicated and are not necessarily related to spore concentrations above the point of deposition.

Van Arsdel using smoke as a tracer indicates that basidiospores of Cronartium ribicola traveling from Ribes bushes on the forest floor to pine needles at night, may be deposited on pines 27 km from their source. This is a result of below canopy dispersal, updrafts over bodies of water and return flows at a higher level. In any event, hyaline basidiospores are unlikely to travel long distances in a viable state since they are most likely killed by UV radiation during the daytime hours.

Most insects are not expected to travel far in the atmosphere because of their large size and settling velocity. Many lepidopterous larvae probably do not travel more than a few kilometers before deposition. Table 3 shows predicted concentrations of tussock moth larvae as a function of distance from the source using a traditional atmospheric dispersion model during typical morning and afternoon conditions. This is not to say that some larvae do not travel further. For example, Collins (1915) found gypsy moth larvae 36 km from the nearest source. Certain meteorological conditions associated with frontal activities also promote travel over longer distances.

Long Distance Dispersal and Deposition

There is still some controversy surrounding the ability of plant pathogens and insects to travel long distances, remain viable, and be deposited in numbers enough to cause impacts. Earlier ideas (Butler 1917) held that long distance transport did not need to be taken seriously into account, but there is evidence that some major pathogens do move long distances. To prove aerial dissemination usually requires interception of migrant spores or incontrovertible association between the source and new colonies. The latter situation has been applied to the spread of agricultural pathogens, e.g. with tobacco blue mold in Europe, maize rust in Africa and banana leaf spot in the Caribbean (Hirst and Hurst 1967). More recently coffee rust travel from Africa to Brazil has been added to the list (Bowden et al. 1971). The best known and documented example of long distance transport of spores themselves is the dispersal of wheat rust urediospores from

Table 3. Predicted downwind concentration of tussock moth larvae (percent of concentration at 10 m from source) in typical morning and afternoon conditions.

Distance from source m	Percent of concentration at 10 m Morning*	Afternoon**
10	100	100
100	5.2	6.4
1000	0.24	0.27
10000	0.006	0.003

* Wind speed = 0.5 m sec^{-1}; stability class C; terminal velocity = 0.252 cm sec^{-1}.

** Wind speed = 3.0 m sec^{-1}; stability class B; terminal velocity = 0.252 cm sec^{-1}.

Mexico to Canada (Stakman and Harrar 1957) although this is rarely accomplished in one step. Most other examples of international dispersal of diseases are man related, including transmission in ships or aircraft (Zadoks 1967).

It is unlikely that many forest pathogens are transported very long distances in the atmosphere, at least in a viable state, since many of them possess hyaline basidiospores. Viable spores of Fomes annosus, however, have been found 360 km from land (Rishbeth 1959). Aeciospores of Cronartium ribicola may also travel long distances and Christensen (1942) indicated that such spores could be carried 480 to 640 km by wind in the Pacific coast region. Further evidence of long distance transport of these spores is supplied by Pennington (1925) who found Ribes infected with Cronartium ribicola 176 km beyond the limits of white pine and infection centers 240 km to 320 km apart.

Is trans-oceanic transport of pathogens possible? Certainly spores have been detected over oceans, but surface concentrations fall off markedly with distance from land. Kramer et al. (1973) found that surface level spore concentrations were less than 3 m^{-3} in air masses of continental origin 300 to 1300 km west of North America. Principal forms of biota included rust and smut spores Alternaria, Cladosporium, ascospores, and hyphael fragments. Basidiospores were not frequently found.

Similar types of biota were found at higher altitudes by Kramer and Helzapfel (1973). At 3,000 m the population over the continental land masses and the Pacific Ocean differed little. Concentrations averaged from 51 to 1.7 m^{-3} on 13 flights which are higher than those at surface levels. Few basidiospores were found at high altitudes. Pady and Kapica (1955) also did not detect any decreases in biota with distance from land on flights from Montreal to London.

In certain cases, especially cases associated with strong thermal activity and fronts, insects may be capable of traveling long distances. Many dispersal studies have been done on continental coastlines. Moths have been known to cross the Atlantic from the United States to Wales (Miles 1955). Diptera appear to dominate in insect samples taken in Alaska, with mites and springtails next (Gressitt and Yoshimoto 1974). These represent the smallest insect groups. In the Barrow area in Alaska the highest concentration of insects was 1.9×10^{-4} m^{-3}.

Few insects are thus expected to travel long distances over oceans, but many may be capable of traveling several hundred kilometers. The forest insect most likely to travel these distances is the spruce budworm particularly in association with frontal disturbances.

THE SYSTEMS APPROACH TO DISPERSAL OF INSECTS AND DISEASES

The systems approach and mathmatical modeling can be used to integrate the various parts of the dispersal system previously discussed, i.e. production, release, dispersion, deposition and impact. Such an approach serves as a tool for pointing out blanks in our knowledge of systems and thus can guide research. In addition, models may be used to predict dispersal and provide information which can be used for control of forest pests.

Disease Simulators

The importance of the plant - pathogen - environment triangle has been recognized for years, but not until the development of simulation models did it become possible to numerically analyze this system in toto, adding in addition the dimension of time. Application of this concept to plant pathology originated with Waggoner (1968) who constructed a simulator for potato late blight. Several other specific crop pathogen simulators were developed in the intervening years. In addition, a general purpose simulator adaptable to a number of plant diseases has been developed by Shrum (1975).

Few simulation models, however, have been developed for forest diseases and insects. Edmonds (1973) constructed a simulator for Fomes annosus, but points out that one of the most difficult problems is the actual prediction of spore dispersion and deposition in forests. This is in past due to the use of traditional atmospheric dispersion models as sub-models in the overall sumulation models.

Traditional atmospheric dispersion models work best over level terrain in neutral stability conditions with moderate to high wind speeds. Such conditions rarely apply in forests which are generally in non-level terrain, and air flows beneath the canopy are extremely complicated. Spore dispersion in Douglas-fir forests is affected by vegetation density with plumes being moved around areas of high density (Edmonds and Driver 1974).

Kinerson and Fritschen (1973) took a different approach to modeling air flow through a forest canopy. They used a direct electrical analog computer. Satisfactory results were obtained with this model. On a larger scale Fosberg et al. (1976) have developed a simple one-

layer model of boundary layer flow for use in mountain valley situations. This model was largely developed for evaluating pollution transport patterns and has been relatively successful.

From this initial analysis of the success of the prediction of spore dispersal one would conclude that success has been somewhat limited. What information, however, is needed for control purposes. Take the situation with Fomes annosus, for example. A forest manager wishes to know if stumps will be infected in a thinning operation. Knowing where the nearest source of spores are located, some approximation can be made with current models as to the distance spores can be expected to effectively spread. Various runs with the model using a variety of meteorological conditions will tell a manager whether the risk of infection is high or low, whether thinning should be delayed to a more favorable season or whether stump treatment is necessary. Predictions, of course, are best close to the source, but become vaguer further from the source, especially in hilly terrain. Similar models can be developed for other forest pathogens.

Insect Simulators

There are fewer examples of the use of systems approach with insect pests. McManus (1973b) developed a conceptual model for the dispersal of gypsy moth larvae. The major difference between the dispersal of gypsy moth larvae and spores of Fomes annosus is the fact that the larvae are generally dispersed above the canopy and spores are dispersed beneath the canopy. The larvae also tend to be released during the afternoon when wind speeds are higher. This situation dictates that prediction of larvae dispersal may be somewhat more successful. There are several complications, however, in that both mechanical and thermal turbulence above the canopy is far different from that over the level terrain. Openings in the forest, for example, create thermal chimneys which may carry insects suddenly aloft. Thus it is expected that prediction of dispersal would be poor on days with strong insolation.

Mason and Edmonds (1974) used an atmospheric dispersion model to predict how far larvae would disperse under various stability conditions. The model predicts that these relatively large particles would travel in large numbers only short distances (< 3 km) although occasional larvae may travel further. A similar situation was encountered by the author in a study of the dispersion of Douglas-fir tussock moth larvae as indicated in Table 3.

Such predictions have implications with respect to control of these defoliators. Knowing wind speeds and directions, stability conditions and the number of eggs in an area, a simulator could be used to predict where most of the larvae will be expected to be deposited. Control methods including chemical sprays or viruses could then be concentrated in these areas.

Prediction of the spread of flying insects such as the spruce budworm may be somewhat more complicated. These insects are released at night and may travel long distances in the upper air. Trajectory analysis has been used for the spread of several insect spores (Hirst and Hurst 1967) and could be used to predict the spread of the spruce budworm.

CONCLUSIONS

Airborne insects and diseases including the gypsy moth, the Douglas-fir tussock moth, the spruce budworm, Annosus root rot, white pine blister rust and southern fusiform rust cause considerable damage to forest ecosystems. These insects and diseases are similar in their behavior in that propagules are produced, released into the atmosphere, dispersed, and deposited on new sites. Their effective spread, however, depends on their arrival in a viable state.

These insect and disease problems cannot be eradicated, but an understanding of how meteorological and biological factors influence the above pathway enables one to pinpoint spots where control measures can be ecologically and economically best used.

Use of mathematical modeling quantifies this approach and can be used to predict spread. This prediction, however, is sometimes difficult in the forest environment, particularly in complicated terrain. Our inability to accurately predict airborne dispersal still remains the weak link in the modeling approach. Certain techniques, including the use of analog models provide hope for the future.

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Weather Influences on Insect Populations[1]

Michael L. McManus[2/]

Weather influences forest insect populations in many ways, some more obvious than others. The indirect effect of weather operating through the host plant may be more critical to the survival of individuals than the direct effect of specific components of weather. Examples are presented that demonstrate how weather affects forest insect populations and various approaches are discussed.

The relationship between weather and the population dynamics of insects has long been recognized - it makes good sense to suspect that insects that oftentimes feed exposed on plant parts, and that cannot regulate their own body temperatures, should be greatly influenced by components of weather. Although there are literally hundreds of publications in entomology that state that weather is an important factor in the dynamics of many species, there are still relatively few that define the mechanism of how weather is affecting each species.

Weather affects insects as individuals, that is, independently of the population density and is thus said to act as a density independent or catastrophic mortality factor. In the 1950s there was quite a dialogue in the literature on the question "can weather control populations?" According to Varley and Gradwell (1974), if a population is acted upon both by a density dependent factor (such as parasites) and a density independent factor such as weather, then the weather determines the changes, but the density dependent mortality factors are primarily responsible for regulating the population about its average level of abundance.

Weather can produce physiological effects on insect populations in four major ways: (1) by modifying the activity of the endocrine system; Many insects of the temperate zone respond to decreasing day length by exhibiting a change in the neurosecretory cells of the brain which induces diapause. Diapause is an arrested state of development where the insects reaction to temperature is switched off. This is a tremendous survival mechanism for overwintering in many species; (2) by directly affecting survival; Frost or low winter temperatures may kill large numbers of many species. Wet weather may induce epizootics of fungi or viruses in insect populations, especially in the spring of the year, or it may have an adverse effect on many species of parasites; (3) by affecting rate of development; Emergence of individuals in the spring and the occurrence of developmental stages in the life history during the summer months can usually be predicted by computing day-degrees over a developmental zero or threshold temperature. Most ecologists are aware of Hopkins' Bioclimatic Law (Hopkins 1919) which fits the timing of phenological events in the USA to latitude, longitude, and altitude. Although this is a relative measure, it has had general applicability in agriculture; (4) it has also been demonstrated that temperature and humidity affect the reproductive rate of some species.

In addition to the effects on the physiology of the population, weather also affects the behavior and activity of insects - this is extremely important to our understanding of processes such as dispersal, which I will discuss later.

This is an extremely broad and complex topic to cover in a limited time frame. I have chosen only to discuss some of the more classical studies that have been conducted on

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forest insects wherein a true weather effect has been demonstrated. At the same time, I will present some of the approaches that have been used in the past and discuss the applicability of their findings.

A long term program to investigate the effects of weather on forest insects was first organized by the Department of Forestry of Canada in 1945. It began with a series of biometeorological studies of the spruce budworm in Canadian forests. The program was expanded and is still viable today.

The Canadians rejected the classical approach to biometeorological studies which concentrated on insect development or mortality, or on an isolated biological event such as emergence. Their approach emphasized the effects of weather on the behavior and activity of insects. Meteorological methods were derived mainly from synoptic meteorology, and climatology. This included descriptions of events in the microenvironment in terms of air mass weather and techniques for determining annual or seasonal changes in the numbers and types of weather systems that passed over large forested areas. Simultaneous laboratory and field studies of insects in extreme situations were also conducted (Wellington et al. 1966).

In the past 30 years, over 100 scientific publications have been produced that are mainly biometeorological - most are concerned with the spruce budworm though many intensive studies were also conducted on the white pine weevil, European pine shoot moth, European pine sawfly, lodgepole needle miner and the forest tent caterpillar, to mention only a few. The Canadians eventually realized that their approach was also too narrow - consequently they have recently emphasized other aspects of insect ecology and physiology that are not usually associated with weather, for example, insect biochemistry and nutrition.

If there is a single leader in the area of bioclimatology, it would have to be Dr. W. G. Wellington, who is now located at the University of British Columbia, Vancouver, B.C. In a classic paper entitled "Atmospheric Circulation Processes and Insect Ecology," (Wellington 1954) he stated that there was an increasing interest in the preventive aspects of applied entomology, but that any preventive program must contain and be preceded by methods for forecasting insect population changes.

Wellington complained that biologists are too preoccupied with so-called density dependent biotic factors (parasites, predators and disease) that affect insect populations, and totally disregard the indirect effects of meteorological factors on the equilibrium of a population by their action on its habitat, its parasites and predators, and on the supply and quality of its food.

He also felt that entomologists usually studied insect populations when they are at or near outbreak levels - this hampers any study of what part of the normal controlling complex went awry and it particularly obscures any basic effects of climate.

To asses climatic influence correctly, it is necessary to study climatic variation during the period preceding or coincident with the beginning of an outbreak.

Wellington (1954) proposed a theory of "climatic release" of a small indigenous population - "in a region where a species exists in small numbers, and in which biotic conditions already favor population growth, no initial increase may occur until seasonal climatic control is relaxed: however, favorable weather may have to recur several years in succession before a major increase in the population occurs."

Wellington believes strongly that serious consideration of meteorological factors have been ignored because of widespread belief that climate is relatively static, so that observed fluctuations are simply random fluctuations about a mean.

Many ecologists warned that weather in the microenvironment differs from the general weather and therefore could not be studied with classical instrumentation. However, particular kinds of microweather are produced by characteristic kinds of general weather. Wellington referred to his synoptic approach to studies of insects and climate: In an area where the insect occurs (a) select two habitats that are most dissimilar; (b) place standard weather bureau instrumentation in the more exposed site; (c) when certain types of weather occur such as frontal systems or air mass passages, an intensive meteorological program is initiated in each area - this gives a range of micrometeorological conditions associated with each weather type; and (d) therefore, only a few days' data/weather type/season are accumulated.

A good example of an application of this approach is the study of the spruce budworm and forest tent caterpillar in the Boreal forests of North America (Wellington 1952). It was noted that spruce budworm outbreaks were preceded by outbreaks of the forest tent caterpillar. Ideal conditions for spruce budworm development occur when the air is relatively dry and clear. Laboratory tests also indicated that the larvae preferred area of

high evaporation. In the field they feed within webbed feeding shelters in buds and expanding shoots. Evaporation in these shelters is optimal when sunny, dry weather persists.

Population increases occurred when the number of cyclonic passages in the late spring and summer are below average and the majority of air masses are of polar continental or polar maritime origin. A southward shift of the whole circulation process is probably influenced by the jet stream in that area.

Conversely, forest tent caterpillar outbreaks occurred when there was a northward displacement of the circulation complex so that an above average number of air masses of southern or southwestern origin occurred in the area. This results in humid, partly cloudly weather during the larval stage and this was shown to be optimal for development and survival of the forest tent caterpillar.

Greenbank (1956, 1957) later verified this phenomenon for the spruce budworm in the Province of New Brunswick. New Brunswick lies in a major exit channel for North American weather systems. Periodic shifts in storm tracks cause considerable annual variations in regional climate. Until recently, there had been two major outbreaks of the budworm in this century. The 1912 outbreak was general to the province and was preceded by a few years of early summer drought. The 1949 outbreak was confined to northern New Brunswick and only that part of the province was subject to earlier drought. He found that a complicating factor was the mass movement of gravid females that were transported by cold frontal storms. This "instant outbreak" potential is now being intensively investigated in New Brunswick.

Now, I would like to discuss some more recent examples of weather affecting forest insect populations.

One of the most interesting recent approaches is a study of the interaction between lodgepole pine, the mountain pine beetle, and its associated blue stain fungi in western Canada (Safranyik et al. 1975). They developed a map of hazard ratings for western Canada based on climatic variables. It's estimated that the mountain pine beetle destroys about 3% of the average annual cut of lodgepole pine. However, the monetary loss is far greater than the volume loss because high-value trees (ca. 80 yrs or 8-10" dbh) are usually killed by the beetle and the fungi.

A map of outbreak chance was developed from the analysis of six climatic variables measured at 42 locations for a period of 20 years.

A. Principal variables

P_1: More than 550 degree-days heat accumulation above 42 degrees F. from August 1 to the end of the effective growing season (Boughner 1964) and more than 1,500 degree-days heat accumulation within the effective growing season from August 1 to July 31 the following year.

P_2: Minimum winter temperatures higher than -40 degrees F.

P_3: Average maximum August temperatures greater than or equal to 65 degrees F.

P_4: Total precipitation during April, May, and June less than the long-term average for these months.

B. Modifying variables

X_1 = Variability of growing season precipitation (coefficient of variation).

X_2 = Average annual water deficit (National Atlas of Canada, 1970).

P_1 was defined on the basis of the following assumptions: 1,500 degree-days is an index of minimum heat accumulation required by beetles between successive peak flights, and 550 degree-days was taken as the minimum heat requirement from peak flight to 50 percent hatching of eggs. If neither of these heat requirements are met, population buildup cannot occur because broods will either be forced into a two-year cycle and overwinter in the pupal and/or adult stages or the majority of broods will have to overwinter as eggs. Eggs, pupae, and adults are more susceptible to freezing than the larvae which is the normal overwintering stage.

In defining P_2, -40°F was taken as the minimum air temperature threshold for population increase because complete mortality results when larvae are exposed to temperatures from -30 to -36° F. for short periods.

In defining P_3, it was assumed that when the frequency of hourly maximum temperatures above 70°F. during August is 5% or less, an extended beetle flight period will result and attack success will decline; flight commonly occurs at temperatures above 70°F.

P_4 is a measure of tree response and of

favorable conditions for beetle development and survival during spring. This variable was established on the basis that high beetle activity followed periods within two or more consecutive years of below average precipitation from April to May over large areas in western Canada.

X1, variability of growing season precipitation, has important effects on the host tree and beetle-fungi complex. The average annual water deficit (X_2) effects the growing conditions for lodgepole pine.

The hazard map, when compare to the distribution and frequency of past outbreaks, is a reasonable representation of the outbreak potential for western Canada. What about the usefulness of this approach for management? Within the two lowest oubreak chance classes, the beetle threat in mature stands is low and therefore the chance of stand depletion is not included in long-range management plans. In areas with the three highest outbreak classes, formulation of long-range management goals and silvicultural practices should include the probability and severity of stand depletion by the beetle. Rotation age can be reduced on better sites, stands can be converted to successional types, or one can recommend clearcutting and regeneration to mixed age classes of lodgepole pine.

The relevance of this approach is that meteorological variables that are biologically meaningful are being used to develop a realistic predictive model that will aid in management decisions.

I would like to turn now to a very different insect problem -- the balsam woolly aphid, a sapsucking insect that infests all true firs. This aphid feeds on the bark cortex of all parts of the tree from stem to twigs and results in severe gouting and eventually tree mortality. Greenbank (1970) described how the ecological characteristics of the insect and the prevailing climate determine the severity of infestation of balsam fir in the Maritime Provinces of Canda. The climate of the Maritimes changes markedly from the coast inland, and Greenbank characterized 3 bioclimatic regions: (2) the coastal regions are maritime climate with mild winters and cool summers; (b) northwest New Brunswick is continental climate with extremely cold winters; (c) central New Brunswick is transitional with periods of mild winters broken by occasional cold winters. He used three parameters to characterize these regions: (a) total summer heat in degree days above 42^{O}F. during the growing season. This determines the number of generations/year and will vary from one to three in the Maritimes, and in the warmer regions of south-central New Brunswick and Nova Scotia where 3000 degree days may occur. This was calculated from field development data; (b) plotted probabilities of winter temperatures over a period of years -- 15 to -25^{O}F. is lethal to the diapausing first stage nymphs; (c) snow cover which is a survival mechanism for those insects that overwinter at the base of trees.

Laboratory and field studies were conducted simultaneously and included thermistor measurement of overwintering temperatures below the snowline and on the trunk and bark scales on branches.

Conclusions:

1. In Maritime areas, i.e. the coastal areas of New Brunswick and Nova Scotia, twig and stem attack occur together and all trees are eventually killed or severely gouted. Survival at the upper strata results in more windblown dispersal and therefore more extensive damage.

2. In continental regions (North Central and Northwest New Brunswick) where severe winters occur, surviving populations are limited to the base of trees below the snowline. With 6" of snow cover, bark temperatures were not recorded below 0^{O}F., while air temperatures above the snowline frequently were recorded down to -20^{O}F. Tree mortality accumulated slowly and gouting was negligible. Infestations remain small and isolated, and dispersal is negligible because of overwintering mortality at the upper strata.

3. In transitional regions (10-60 miles inland) populations behave as in Maritime area when mild winters occur. However, periodic severe winters occur every few years and this tends to decimate the aphid population so that trees may recover.

One of the most important aspects of the relationship between weather and the population dynamics of forest insects is the interaction through the host plant. It's amazing to me that forest entomologists are finally getting around to looking at the complete system - the interaction between insect, host plant, and weather. There has been a resurgence in this research area and it has been long overdue. Though T.C.R. White (1969) has only recently published on weather-induced stress of trees associated with outbreaks of forest insects, the idea is not new. Charles Darwin, in his classic "The Origin of Species" in 1859 stated and I quote ..."in the struggle for existence the indirect effect of weather operating through food supply is more important than its direct influence on the animals themselves." It has taken us a long time to investigate this hypothesis.

Much has been written about the interaction between weather and food, but the emphasis has been placed on changes in the distribution and abundance of food during different seasons (Wellington 1957). Recent research suggest that the effect of weather on the quality of food may be the controlling factor in many of our insect problems (White 1974, 1976).

There have been two widespread and severe outbreaks of a psyllid (sapsucking insect) on eucalyptus in Australia. Outbreak periods were characterized by unusually wet winters and unusually dry summers. Soils in this area are poorly-drained and are susceptible to waterlogging in winter and to drought in the summer.

White developed a "stress index" obtained by transforming the rainfalls for summer (December-February) and for winter (April-October) each year to standard normal deviates about their means. The relationship of these values to the long-term mean is not relevant--the contrast between winter and summer in the same year is important. Stress index was positive when the summer was dry relative to the preceding winter.

There were two periods since 1900 when the stress index for south-eastern Australia increased rapidly to high positive values - and that was when outbreaks occurred. When he plotted data for the rest of Australia, the same relationship held up quite well. Between outbreaks, population of psyllids became so sparse that only a few persisted on individual trees.

White suggests that the causal explanation of why outbreaks are related to stress indices is as follows: when a plant is stressed, especially water stressed, there is a complex change in the quantity, distribution and composition of its nitrogen content. A general decrease in protein synthesis and conversion of existing protein into water-soluble forms takes place. There is an increase in total nitrogen in aerial parts of plants and a decrease in the roots in response to dehydration. This may result in either a general quantitative increase in the amount of nitrogenous food available or in the relative proportions of one or more of the amino acids in the phloem sap. Nitrogenous food is essential for young, rapidly developing animals.

White then demonstrated in the laboratory that the phloem sap of healthy trees (unstressed) is actually unsuitable for survival of immature psyllids. They would insert their stylets and initiate feeding but eventually died with the stylets still inserted.

White (1974, 1976) has also applied this weather-stress hypothesis to explain outbreaks of looper caterpillars in New Zealand and of other defoliating insects. I am convinced that this explanation is sound although there may be more involved than a simple nitrogen relationship in the host. The most critical period for most defoliating insects is when they must establish on foliage after they hatch and/or disperse in the spring. We assume that if foliage is abundant, it is acceptable to the insect. I suspect this is not true although we lack positive proof to substantiate this theory. For example, in our study of the gypsy moth, we often predict from egg mass counts that complete defoliation is inevitable - however, many times defoliation does not result and we have not been able to explain why - certainly biotic agents have not been responsible. If in fact the foliage was not acceptable, the newly-hatched larvae would eventually starve, and we have no way of quantifying such an occurrence.

White's stress index may be an over-simplified approach. Recently Kalkstein (1976) attempted to evaluate effects of climatic stress upon outbreaks of the southern pine beetle. He suggested that climatic variables should be expressd as variables derived from the Thornwaite climatic water balance. This considers the soil moisture factor and also evaluates the potential evapotranspiration, which is an estimate of the amount of moisture lost from a vegetation covered surface. This is probably a much more accurate and realistic way to evaluate stress on a tree or plant.

I did want to emphasize one good example of the effect of weather on insect behavior, specifically dispersal. Many of our major forest insect pests disperse passively as windblown larvae on silken threads - this includes the spruce budworm, gypsy moth, and Douglas-fir tussock moth. In my research on dispersal of gypsy moth larvae, we encountered a situation in the field where dispersal in the spring of 1974 was literally shut-down. We were monitoring egg hatch and had established a series of elevated samplets to entrap dispersing larvae. However, just as peak hatch occurred, a weather system moved through the study area resulting in low temperatures and cloudy, inhibited activity and dispersal behavior. Dispersal never did commence and we caught few larvae in our traps. This has a deleterious effect on survival and also retards redistribution and spread of the larvae in the general area.

Though I have limited my discussion to forest insects, the best example of weather affecting dispersal of insects involves aphids and leafhoppers that transmit diseases to cereal crops. Wallin et al. (1967) demonstrated that low-level jet winds that flow from the southern plains into the North Central states in April and May, are responsible for the mass transport of these species over hundreds of miles.

CONCLUSIONS

A synoptic biometeorological approach should be included in our studies of the population dynamics of forest insects. Additionally, simultaneous studies on the effects of stress on the quality of the host should also be included in such investigations. The examples that I have discussed in this presentation suggest that weather does affect insect populations in many ways. Why have biometeorological investigations been so seldom employed in the past? I have some observations and some suggestions.

1. We are always looking at the data after the fact. Standard weather data can usually be obtained from the past, but our quantitative measure of historical insect population data has been inadequate and is usually only an indication of what really occurred.

2. Analyses of historical weather and insect population data can produce predictive models and demonstrate cause-effect relationships; however simultaneous field and laboratory studies are needed to identify the mechanisms through which weather is affecting the population.

3. Support has been lacking for long-term research. Even the USDA combined forest pest programs on the gypsy moth, tussock moth and southern pine beetle, which have been a tremendous stimulus to accelerate research and to attain specific objectives, cannot provide the solution to this problem because they are funded for a 3-5 year duration. We need a continuing research program in order to obtain the quantity and quality of data required.

4. An interdisciplinary approach is needed. I propose that our lack of progress in this field stems from the fact that entomologists have been uncomfortable with meteorological data, its interpretation and the instrumentation and methodology that may be required to obtain it. Similarly, most are not equipped to conduct companion studies in tree physiology or insect biochemistry. An entomologist, working with a meteorologist and a biochemist or physiologist should be able to design a research program that considers the effect of changing weather on the quality of both the host and the insect population that is dependent upon it for survival.

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Meteorology and Pesticide Application[1]

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Abstract.--Problems in aerial application of pesticides to forests are described with special reference to meteorological factors. Field experiments, pilot projects, and operational projects are considered. All require weather forecasting to schedule spraying. Needs describing equipment and methods to control or measure spray behavior from release until arrival at the ultimate target are discussed. Figures are presented with several constraints that define a spray window showing best drop-size range and atmospheric conditions for spraying. The constraints have not been established quantitatively and show the need for additional meteorological research and development. A need has been demonstrated for a spraying strategist, who may or may not be a meteorologist, but will require new tools from the meteorologist.

INTRODUCTION

I've been involved in developing equipment for aerial application of insecticides in western forests since 1964. I certainly welcome an opportunity to share some thoughts I have developed over this period, particularly in the unfilled needs in delivering pesticides from the air to the forest canopy.

I would like to begin with a quotation from Dr. Peter Southwell, who is with the School of Engineering, University of Guelph, Ontario, Canada. This is a quotation from an address given by Dr. Southwell at the Fifth International Agricultural Aviation Congress in Warwickshire, England:

"The evidence suggests that precise definition of target surface and thence prescription of the optimum droplet size and number of droplets for a particular circumstance could lead to tremendous increases in the efficiency of pesticides usage. In order to achieve this, though, we need to understand a great deal more about the spatial dynamics of insects, about micrometeorology within and above crop canopies and about the behavior of droplets. The first of these paths to progress is the preserve of the biologists amongst us, and their colleagues. The second emphasizes the urgent need for a much greater input to bio-aeronautics by the meteorologists. The third path lies in the territory of our physicists and aerodynamicist friends, and I hope they will be persuaded to collaborate with the meteorologists in studying the performance of foliage canopies as a droplet filtration system."

Dr. Southwell is speaking about aerial application in general, including agricultural crops, forestry, and public health, but I think that his remarks are particularly pertinent to our forestry application. Dr. Southwell very pointedly mentions the need for interdisciplinary cooperation. He points out not only the need, but the possibility of tremendous progress. This progress, however, is dependent on interdisciplinary cooperation and he especially emphasizes the need for the meteorologists as well as the physicists and aerodynamicists.

Here are some observations on the state of the art in aerial application within the United States. I do not know of any forestry aerial application group within the United States, conducting comprehensive research and development, that has a full-time meteorologist on its staff. Some of the organizations doing what I would call comprehensive research and development have people from other disciplines

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who work in the field of meteorology, who take meteorological measurements, who attempt meteorological interpretations, but are not prefessional meteorologists.

We know that one of the most important aspects of aerial application in forestry is selection of proper drop size. We also know that selection of proper drop size and production of that particular drop is one of the most, I might say controversial, but perhaps I should say most discussed questions. For most forest insects and pesticides the entomologist cannot tell us the precise drop size that he would like to deliver to the target. Even if the entomologist could specify the drop size, the meteorologists and physicists cannot tell us precisely how to deliver that drop size to the target; and even if the meteorologists and physicists were able to tell us how to deliver this drop size, the engineer cannot tell us how to produce this drop size and what the effect of aircraft wake is upon delivery of the drop.

Dr. Southwell says that there is a tremendous area for progress. I mentioned some of the lack of progress and I would like to continue to discuss the problems from the standpoint of delivery of insecticides. I would like to go on to a discussion of some of the progress made in solving these problems and how this variety of problems might be organized for an efficient attack by those biologists, scientists, and engineers. Finally, I would like to draw a scenario of how the future spray project might be conducted when you gentlemen and your colleagues have solved some of these problems and have made the solutions available to the forester who is charged with the responsibility for managing the insect population.

I am not here to ask you as meteorologists and specialists in fluid dynamics to solve all of the aerial application problems; I am certain that efficient solution of the meteorologically related problems cannot be attempted without some knowledge and appreciation of the variety of problems that beset the aerial applicator. Therefore, I am going to present an entire array of problems and leave it to your judgment which ones you feel the meteorologists can most efficiently attack.

PROBLEMS AND PITFALLS

Chemical sprays have been used to control insect and disease in agricultural crops for many years. Literature abounds with results of research and new equipment as well as techniques developed for spraying cropland. From the standpoint of control, aerial chemical spraying of agricultural cropland has been very successful. Techniques and equipment developed for aerial spraying of croplands have been adapted to aerial spraying of the forests; sometimes successfully and sometimes unsuccessfully. Forest spraying presents many problems not found in normal agricultural spraying: The target is a dense three-dimensional canopy; the terrain is usually irregular; convective winds are frequently prevalent; the aircraft cannot fly close to the crop; the crop is usually a low-value crop compared to agricultural crops; there is frequently high-quality water nearby; there is difficulty in marking ground locations.

Let us look at some problems facing an applicator spraying forest insect larvae in the western United States:

1. Because of the concentrating effect of mountain valleys and canyons, significant concentrations of insecticides can be carried several miles.

2. Instead of falling a few feet as in the case of cotton spraying, forest insecticides must travel 50 to 250 feet vertically to reach a target. Losses, due to evaporation, become more significant both in terms of greater drift and loss of insecticide.

3. The dense forest foliage may capture all of the insecticide within a few feet, resulting in only one side of the tree being sprayed.

4. On the other hand the drops may be so small that they are deflected around the target by aerodynamic forces.

5. Some lateral displacement of the spray is beneficial, but if the displacement is excessive the applicator cannot predict where it will reach the forest and has lost effective control of the spray.

6. In his zeal to prevent excessive lateral displacement, the applicator may select drops so large that too few numbers of drops are available for effective coverage.

7. It is difficult to fly evenly spaced swaths over large, irregular tracts of forest having few roads or identifying boundaries.

8. Steep slopes present several problems. The actual surface area is greater than shown on a map, the downhill side of the boom may be 50 feet higher above the trees than the uphill side of the boom. Flight path and direction are limited because the aircraft cannot climb steep slopes, instead the aircraft usually flies contours.

9. Rough, irregular terrain is usually associated with steep slopes. If the applicator flies a level path his altitude above the terrain varies continuously; if instead he follows the terrain, roller coaster fashion, his speed and application rate vary continuously.

10. In an effort to obtain better coverage, the applicator may increase the volume of insecticide carrier without giving adequate consideration to the lethal drop size, requiring hundreds of drops to kill a larva rather than one drop.

11. The aircraft wake, whether it be wingtip and propellor vortices from a fixed-wing or rotor vortices from a helicopter are a major influence on the spray behavior. Small drops are entrained in this cloud and transported in a manner similar to smoke ring movement. Other larger drops fall independently of the vortex but are not readily visible. Thus, the applicator may be misled by observing the visible cloud.

12. In 2 hours of morning spraying the stability conditions usually vary from spraying under an inversion to neutral or unstable condition. The applicator will not be aware of these changes.

SOLVING APPLICATION PROBLEMS EFFICIENTLY

To see the contributions that meteorology as a science can make towards these problems I think it is well to establish some levels of usage. The natural development for research leading toward applications in the field of insecticides within the Forest Service begins with laboratory screening. The second step is field experiments with the most promising laboratory materials taken to the field and evaluated on a small scale within the forest. Small scale is generally in the 40-acre spray block category. The next step would be a pilot control project. Here the promising candidates from the field experiments are taken to the field and applied on a large enough scale to simulate the problems that would be encountered in a control project. The equipment must be large enough to be used on a larger scale control project. Then candidates that have passed these phases, have met the requirements of the Environmental Protection Agency, the Department of Agriculture, and the Forest Service are available for control projects which are a management tool of the forester.

At the first level of usage, laboratory screening, we see a place for the meteorologist in assisting the biologist in the design, construction, and operation of the spray chambers and in the conduct of wind tunnel experiments. In field experiments the meteorologist can be expected to play a very important role because usually we have a large number of chemicals or pesticides, the plots are small, and there is a need to demonstrate that comparisons of various pesticides have been conducted under sufficiently similar meteorological conditions to provide a proper comparison. Since the spray plots are small, delivering the material to a small area is frequently much more of a problem than when substantial amount of drift and swath overlap is useful on a large spray project.

In a pilot control project, one of the important roles served by the meteorologists is in providing weather forecasting. These projects are usually quite expensive and yet they provide no direct economic benefit to the forest manager because they are not established to control insects, so the minimization of cost is very important. The meteorologist can give us accurate weather predictions so that the materials can be applied under the desired conditions and the mobilization of equipment and manpower is done on an efficient basis.

A further important role is as an advisor to the project officer on strategy and tactics for delivering the insecticides. This has been a role that we have seldom seen a meteorologist in but one that I think is going to be of increasing importance.

The control project itself has all of the same problems that a pilot control project has, but in addition it is probably more subject to public criticism and scrutiny. It involves dispersion of much greater amounts of pesticides, therefore every phase of the application from delivering the minimum amount of insecticide to a given area and concern with off-target risks are extremely important. Again there is a role for a spray strategist.

NEED FOR RESEARCH AND DEVELOPMENT IN EQUIPMENT AND METHODS

We do not know all of the things that need to be measured in the field and we do not know how frequently or where they need to be measured. However, we can make some general statements.

Battery-powered Equipment

Equipment should be portable and since we need information from several locations it should be as inexpensive as possible, compatible with the quality of information. There is probably a need for a telemetry system that can accumulate real time data from a variety of points within a spray area and transmit it to the project director. We also know that simply making meteorological measurements at or near the ground level is not sufficient; that there is a definite need to have some information in the regions above the canopy and near the release line of the aircraft. We've worked with two types of system here at the Equipment Development Center in Missoula: Tethered balloons which either transmit information via a wire or via a radio signal. We've also used portable towers and it has been my own experience that the towers that are available are too slow, too cumbersome, not sufficiently portable to be useful. My own opinion is that for measurements in the region above the canopy, tethered balloons are definitely preferred.

Some of the things that affect spray behavior are turbulence, windspeed, wind direction, and temperature; here again not just at ground level but the entire region from release at the aircraft to the impaction on the target.

Weather Forecasting

Under Methods Development, the first item to consider is forecasting. For most of us nonmeteorologists when we think of meteorology we think of weather forecasting. As a result of the efforts of the combined forestry and meteorology groups there are available the tools and the administrative procedures that have been developed in connection with fire control to provide weather forecasting service to aerial spray applications. We have found fire weather forecasting to work extremely well. The quality of weather forecasts is going to depend generally upon developments on a much broader scale in the state of the art in knowledge in forecasting weather. So perhaps one of the biggest improvements that might be made is in providing additional information to the weather forecaster. Can we provide additional, faster, more specific information about the particular spray sites to the weather forecaster so that he can give us improved forecasts? Generally there are two periods when we expect a forecast from the meteorologist--(1) in the evening before spray day, final decisions are made as to what areas will be sprayed, where the people will be deployed, how much material will be mixed, and at this point it is very important to have the most up-to-date forecast information for decisionmaking about the following day's activities; and (2) just prior to spraying. Now, unfortunately, this usually occurs at 4:00 or 5:00 in the morning. But at this point new weather patterns may have developed and a decision must be made quickly on whether to spray or not to spray that day. So it's very important that we have the weather forecaster and his best knowledge and judgment available to us at that particular time.

Air-to-Air Spraying

I would like to touch briefly on air-to-air spraying. To the best of my knowledge there has been no air-to-air spraying of forest insects conducted within the United States. However, an extensive research program is being carried out in New Brunswick, Canada. The basis for the air-to-air spraying of the spruce budworm is to spray the adult moth before she can lay her eggs in a previously uncontaminated area. It involves radar tracking of clouds of moths, as well as the tracking of wind systems, followed by predictions of where within the air space to deliver a swath of pesticide that will make contact with the adult moth in the air. In this type of operation even more than in normal spraying, the close cooperation between the biologists, meteorologists, engineers, and aerodynamicists is very important. On this topic I would leave you with the question that if air-to-air spraying of the spruce budworm in the Province of New Brunswick is successful, should the similar technique be investigated for application within the United States, both in eastern forests and in our western mountainous region? Here the most important starting point in the air-to-air spraying is understanding the activities of the moth as related to time, space, and meteorological conditions. Therefore I think we probably could expect the leadership to come from the biologists.

Control of Drift

There has been a large amount of research done in the control of spray drift and contamination of nontarget areas by the agricultural researchers. Most of these tests have been done in relatively flat agricultural areas. Within our mountainous terrain I am sure that many of the same techniques can be applied; certainly the same type of monitoring equipment, but within the mountainous regions we're sure that insecticide drift is concentrated by the

channeling of airflow through canyons and valleys.

This would appear to be a formidable array of problems. It is also a tribute to the aerial applicators that they do carry on successful spray projects despite these problems and the lack of knowledge in some of the areas.

AN APPROACH TO ORGANIZING THESE PROBLEMS

In figure 1 we show the effect of a droplet being carried so far away that it is essentially beyond the control of the applicator. Here we have a plot of droplet diameters versus windspeed above the canopy. The shaded area to the left is the area in which the drops would be carried too far. I've somewhat arbitrarily chosen 1,000 feet as too far. In some circumstances it would be more and in some less. We see that there is an area on the right within which the drops can be contained and an area to the left which we want to avoid.

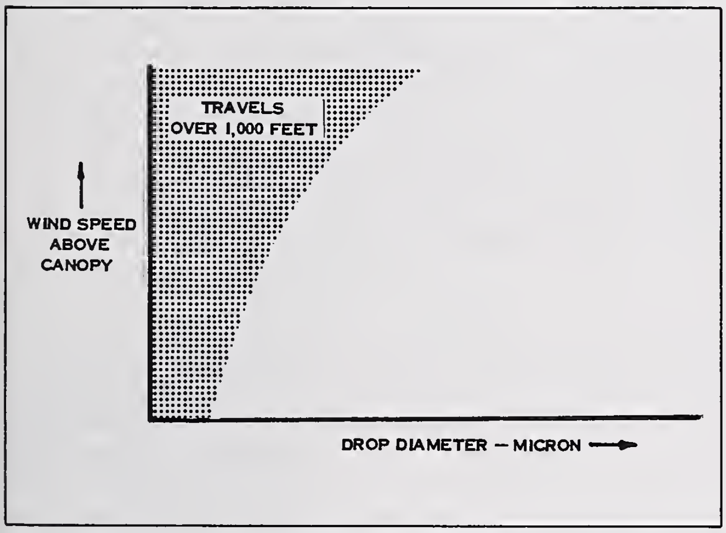

Figure 1.--Excessive swatch displacement.

Figure 2 shows another aspect of the problem. This is a representation of the fact that the droplets will not penetrate the canopy. That is they will be very effectively filtered out by the first foliage that is encountered and cannot be uniformly deposited throughout the canopy. In this case the permissible area is on the left. The avoided area is on the right and again it's a plot of drop diameter versus windspeed above the canopy.

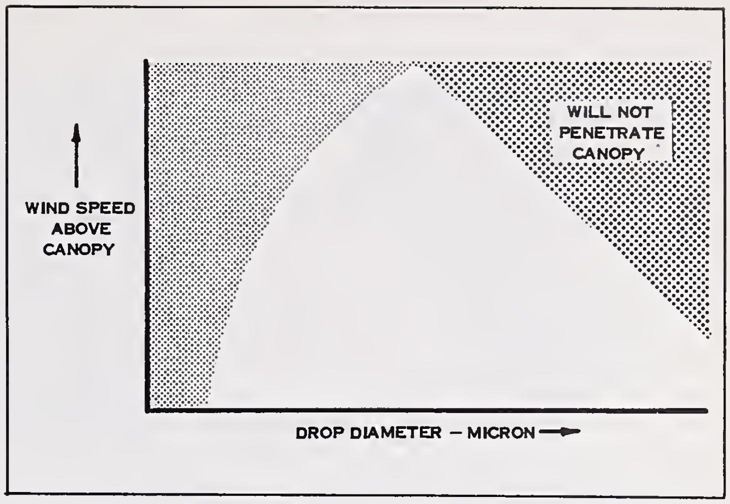

Figure 2.--Drops too large to penetrate canopy.

In figure 3 we have the same coordinates, but we demonstrate the area in which there are not sufficient drops available to provide adequate coverage. This is of course based on some reasonable amount of total volume of material being delivered. Again the area on the left is suitable; the area on the right is to be avoided.

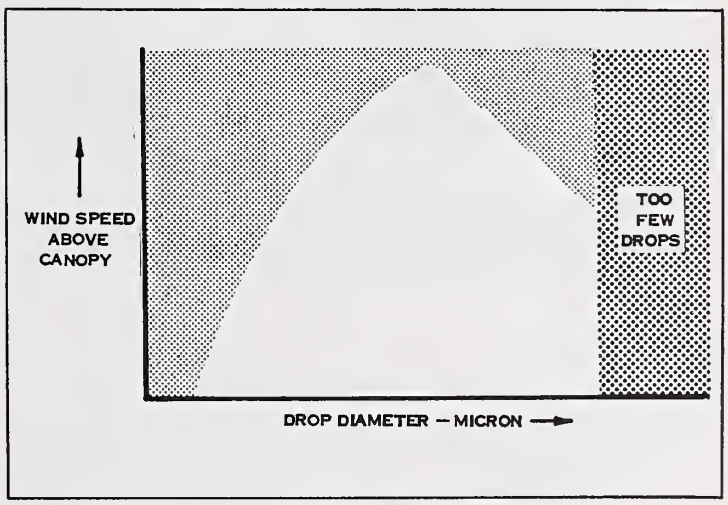

Figure 3.--Too few drops for coverage.

Figure 4 shows relationship between windspeed and drop size for one value of turbulence. In figure 5 we show the area where because the windspeed is too low and the drops are too small, they will not impinge on the target. In this case the target might be considered to be either foliage or an insect. The area on the right is permissible; the area on the left is to be avoided.

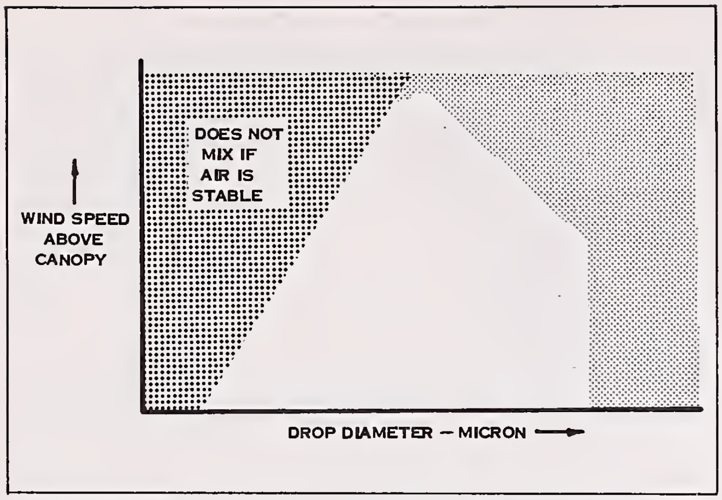

Figure 4.--Lack of turbulence affects deposition.

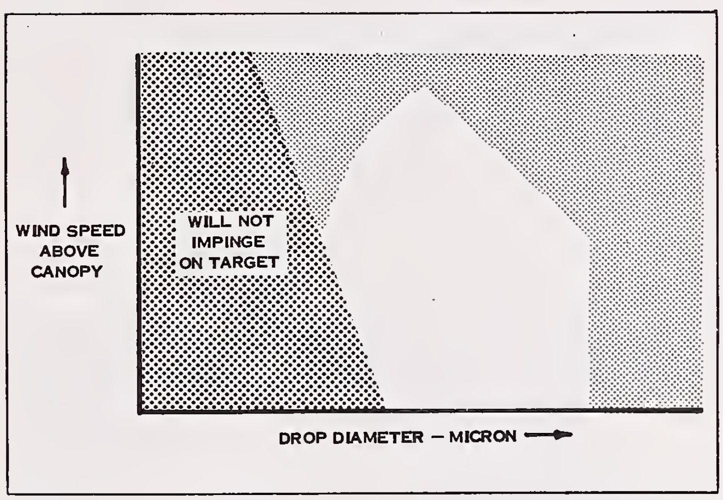

Figure 5.--Drops are deflected around target.

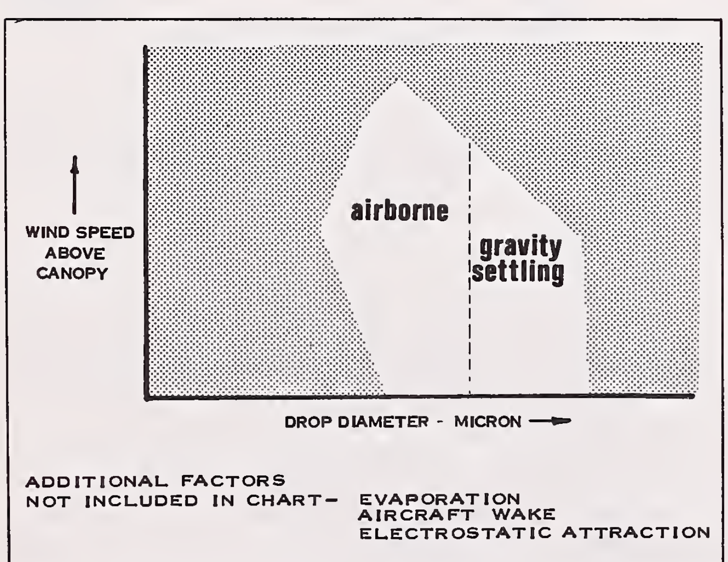

Figure 6.--Envelope of optimum drop size.

In figure 6 we chart all of these curves on the same graph we find that in the center is the permissible area bounded by several areas that are not useful. Here again notice that we have not placed any values on drop diameter or values on windspeed. However, we know a general range for these values and demonstrate that when all of these constraints are considered together there is one open area that is permissible. We also feel pretty certain that this permissible area is broken up into two areas. On the left side the drops are so small that they are principally airborne. Their terminal falling velocity is so low that they are essentially carried wherever the wind takes them; whereas the right side represents larger drops. These large drops are affected by air movements but their arrival at the target is primarily through gravitational settling.

These figures demonstrate the possibility of a rational approach to this entire problem where a multitude of factors can be considered together and it also shows that the problem is complicated by the fact that the physical behavior of the drops in the optimum range is essentially governed by different sets of equations; one being the airborne particles and the other being the particles subject primarily to gravitational settling. I would also like to point out that there are other factors that affect the optimum drop range that are not included: Evaporation, effect of aircraft wake, and the electrostatic attraction of the ground and foliage for the drops.

Spray Strategist

There are some very severe constraints imposed upon a large operational spray project. The period during which the insect is susceptible to the material being applied is relatively short. The time of day and number of days with weather suitable for spraying may be relatively brief. The number and types of aircraft that are available for a short duration project are definitely limited. These are constraints that very little can be done about., However, at the same time, by understanding the physical phenomenon that are governed by basic scientific principles we can spray more effectively, reduce damage to the environment, and in some cases increase the period of time available for spraying.

I feel that the principles involved and the expertise are sufficiently complex to warrant the training of a spray strategist. I'm not suggesting that the spray strategist be a primary title, nor am I suggesting that the person need to be a meteorologist or physicist or engineer. However, I believe that the physicists, aerodynamicists, engineers,

meteorologists, entomologists must develop the body of knowledge and ultimately provide training to a spray strategist who will be available as a staff position to a project control officer.

Sample Spray Project

During the Northern Region pilot control project for spruce budworm in western Montana in June 1976, we applied some of the principles of spray strategy. We think that the principles were applied successfully and contributed to the success of that particular spray project. The principles and body of knowledge that are necessary for good spray strategy have not been completely developed. However, I would like to give you some examples of how spray strategy might be employed.

This was a spray project that was conducted on National Forest land that was rough, steep, irregular terrain. Spraying followed the conventional practice of spraying early in the morning and continuing spraying until either a plot was completed (these plots were about 2,000 acres), or until the winds appeared to be unfavorable. The spraying was done with a turbine-powered helicopter with rotary atomizers.

Now, some examples of what we did:

- We made a study of seasonal weather patterns in the area.

- The pilot was required to fly a reconnaissance of each spray area prior to the day of spraying, and submit a map of his selected direction, length and order of spray swaths.

- A meteorologist reviewed the flight plan and gave the pilot an estimate of windspeed and direction and estimates of when windspeed and direction would change.

- Ridges were sprayed during the first 30 minutes of daylight when downslope winds were in effect. It is almost impossible to spray ridges after upslope winds are well developed.

- Windspeeds were measured both at ground level and 50 feet above the canopy during spraying.

- Whenever possible the aircraft was flown crosswind to enhance overlapping of swaths.

- Based on model calculations the pilot was instructed how much to offset from the spray boundary to compensate for swath displacement.

- Special attention was given to areas that had converging gradient and slope wind fields.

- Actual swaths flown by the spray aircraft were plotted on an aerial photo by an observer in a chase helicopter.

These are a few of the things that can be done based on today's knowledge and equipment.

For the future one can imagine many things within the realm of today's technology.

- Electronic guidance for spray aircraft that also operates a plotter at ground station to show swath patterns on a map.

- Computer generated maps of predicted drainage wind flows for each hour of the day.

- Several remote locations where windspeed, wind direction and temperature are measured and automatically transmitted to a central station.

- Spray equipment that can be quickly adjusted to provide drop sizes to suit a newly observed meteorological condition.

- A remote sensing monitor for detecting excessive off-site spray drift.

- But perhaps most important, a well trained spray strategist who can access this information, interpret the information and provide the project director the best guidance on how to deploy the spray equipment.

CONCLUSIONS

1. There is a great potential for improving aerial delivery of insecticides.

2. Most of the major problems are readily identifiable.

3. Technology for solution of the problems exists but must be applied in a creative, innovative manner.

4. Timely efficient solutions require a comprehensive program directing the efforts of an interdisciplinary team.

In closing I would like to once more quote Dr. Southwell:

"We need to keep our feet on the ground, as well as our head in the clouds."

A Canopy Penetration Model for Aerially Disseminated Insecticide Spray Released Above Coniferous Forests[1]

Bruce R. Grim[2]

John W. Barry[3]

Abstract.--A mathematical simulation model has been developed which predicts the penetration and verticle distribution of aerially applied insecticides through coniferous canopies. Model input includes forest and tree types, spray characteristics, and meteorology. Plots were constructed of model predictions and observed data from a U.S. Forest Service pilot project. Model behavior is relatively consistent with observed data.

INTRODUCTION

Previous experience in the development and implementation of aerial dissemination techniques for coarse aerosols and sprays has disclosed the need to minimize spray drift and increase the efficiency of spraying in terms of cost and insect control. Effective use of mathematical modeling techniques, which establish relationships between the many factors effecting spray operation, has resulted in the capability to optimize flight patterns and spray strategy, and to predict the success or failure of a proposed spray operation.

Penetration of forests by fine aerosols has been addressed by Calder (1961); however, penetration of forests by droplets with an appreciable fall velocity has had limited attention. A theoretical study by Johnstone, Winche, and Smith (1947) addressed the problem of droplet impaction on verticle and horizontal surfaces. The study, however, did not attempt to relate specific forest parameters (i.e. tree stand, density, foliage density, tree height) to the amount of material penetrating the canopy.

The U.S. Army Dugway Proving Ground (1971) prepared a prediction study with a line source model for the U.S. Forest Service. The model accurately predicted that the amount of insecticide material planned for release over the target was insufficient to produce the desired insect mortality. Prior to field trials conducted by the U.S.F.S. in the Bitterroot National Forest during 1973, (Dumbauld and Cramer 1973) prepared predictions of downwind deposition of insecticides. These predictions were used successfully by the project officer in deciding where the release should start and end to achieve maximum deposition within the spray plot. These predictions were for above-canopy deposition. Problems related to physical penetration of the canopy by the insecticide were not studied, as there was no model available at that time.

The objective of this study was to develop a model for predicting the penetration of insecticide sprays through a coniferous forest using forest characteristics as input to the model.

METHOD

This study relates canopy penetration of droplets 50 micrometers and larger in diameter to forest characteristics and wind velocity. The selection and description of the tree and forest types was a very critical part of the

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1/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.

2/ Meteorologist, U.S. Army Dugway Proving Ground, Dugway, UT.

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model development. For reasons related to practical application of the model, only forest measurements which were easily obtained from photographs or on-site inspection were used as input to the forest characteristic part of the model. The fall velocity and collection efficiency of four drop sizes were used throughout the construct of the model. Wind speeds between 0 and 5 meters per second were used in developing the model while actual field data were used in comparing model predictions to observed data.

Meteorological prediction models were utilized as a modeling framework since these in general are mass continuity expressions that specify the timespace distribution of material which has been released into the atmosphere. Specific application of this model type was used to predict insecticide spray concentration and deposition patterns from known spray physical properties, emission and dissemination factors, meteorological factors, and forest characteristics. The generalized nature of the prediction model is an important feature of the basic model format and is intended to be univerally applicable to all spray problems by simply varying the number and values of the input parameters (Barry, Dumbauld, Cramer 1975).

Twelve trials conducted in the Bitterroot National Forest, MT, by the U.S.F.S. were used as the data base. Zectran, an oil base insecticide, was used in six trials, and the bacterium Bacillus thuringiensis (B.t.) suspended in water was used in six trials. Each trial consisted of helicopter spraying, by the swath method, a 40 acre plot. Detailed information on the conduct and results of these trials is contained in a paper (Barry, et al. 1975-b).

Release of liquid insecticide spray from aircraft can be characterized in general by several distinct phases as illustrated in figure 1. In the initial stage of spray release, the droplet spectrum is determined primarily by nozzle configuration and wake turbulance effects. As the material drifts downward toward the canopy, wind drift and evaporation effects take place. Concurrently, the droplets enter

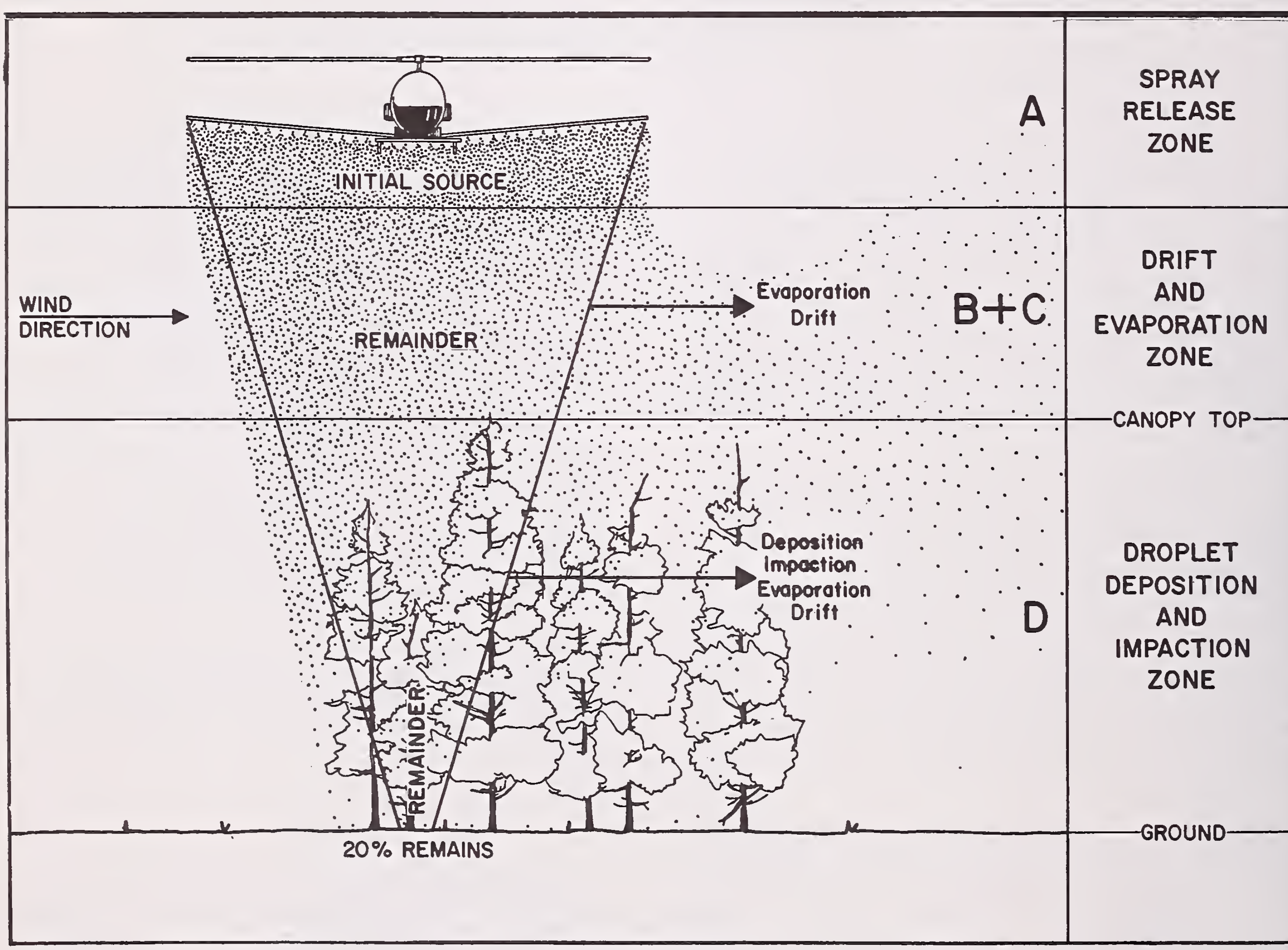

Figure 1.--Physical process involved in insecticide spray release.

the canopy and either deposit or impact on the vegetation or find their way to the ground.

The effects as illustrated in Zones A through C of figure 1 have been modeled successfully for droplets, 50 µm and above, with appreciable fall velocities in open terrain and above forest canopies. There is no known model which predicts the behavior and effects of spray droplets into and within the forest canopy (Zone D).

This study was directed to the scavenging effects of the forest on the spray droplets as they fall through the foliage. Each droplet size was considered to follow a trajectory through the forest to the ground, based upon the droplet's fall velocity and the wind profile in the canopy. This trajectory may or may not intercept a vegetative element depending on the forest, characteristics of tree stand density, foliage density on individual trees, and collection efficiency of various vegetative elements for different sized droplets.

In previous work (Barry, Dumbauld, Cramer 1975) a measure of this scavenging effect was defined as the penetration ratio. It is the ratio of droplets of a given size (diameter) recovered on the ground beneath the canopy to those entering the top of this canopy. Thus, for a given size droplet the penetration ratio is:

$$PR = \frac{\text{Number of droplets recovered below canopy}}{\text{Number of droplets above canopy}}$$

To determine the number of droplets below the canopy, samples are obtained from beneath sample trees throughout the spray block.

The number of droplets at the top of the canopy is determined by measuring recoveries in an open area outside the influence of the forest. It is assumed that the number of droplets which fall directly to the ground is the same which is presented to the top of the canopy. In making these measurements, it is essential that the open area sample represent a recovery which has not been scavenged by the forest. The model proposed in this study computes this ratio for various sized droplets and for various levels in the canopy; that is, the numerator of the above expression is not restricted to ground level, but is computed for 9 levels within the canopy. The model provides a measure of the spatial distribution of mass within the canopy. It is basically independent of the initial spray distribution in the sense that it only provides canopy penetration ratios, not ground distribution patterns as generated by the usual mass transfer models. These penetration ratios could, however, be readily combined with the mass transfer models to provide ground distribution patterns for various droplet sizes beneath the canopy.

The model basically uses the following methodology:

1. Generates a simplified forest
    a. Specify size and shape of any tree envelope.
    b. Specify number of stems per acre.
    c. Specify foliage density type.
    d. Place trees randomly.
    e. Specify collection efficiency.
    f. Specify wind profile.

2. Simulates spray penetration of forest
    a. Compute trajectory.
    b. Examine for impact location.
    c. Tabulate penetration ratios.

Trees are simulated in the model by a tree envelope, which is adjusted to the size and shape of the average tree. Tree shape is determined from photographs or physical measurement of the selected forest. The model is capable of simulating up to three different tree shapes for any single run, thus multi-species of multi-storied canopies can be simulated. The number of trees per acre per species is also determined from forest measurement or aerial photography.

The probability that the trajectory of a particle which passes through a tree envelope will intersect a vegetative element is a function of the foliage density per tree. This probability must vary from a value near 0 for a completely defoliated and very slender tree to near 1 for a very dense foliated tree. Estimation of this value is presently subjective with the establishment of four foliage density categories. Having specified the above parameters, a simulated forest can be generated using a random-number generator to place the trees according to stand density.

The canopy is then divided into four equal height intervals for assigning an average wind velocity within each interval. The wind velocity in each interval is combined with the fall velocity for each particle size of interest to compute the trajectory vector for the particle in the height interval.

With the trajectory for a specified droplet of size determined, the model computes the height above ground where an intersection occurs between the particle and a random tree envelope which lies along the trajectory. If such an intersection occurs, the probability that the particle actually impacts on the vegetation is computed. In order to do this, three factors are taken into account: fall angle of the particle; foliage density; and collection efficiency associated with that size particle.

Assumptions made concerning the above three factors are critical to the overall penetration ratios obtained. The assumptions made in this study are considered to be only a starting point for further investigation. It was assumed that the probability of intersection is a power function where the exponent is the secant of the fall angle. The probability of penetration (PRPEN) which was assigned to the tree envelope was based upon a view in the horizontal, that is, it provides the probability of intersection for a fall angle of 0^{o} to the horizontal. For steeper angles, the path length through the tree is generally longer and the filtering effect on the particles would tend to grow exponentially with path length. However, the path length is limited by the size and shape of the tree.

Collection efficiency as a function of droplet size is another gray area in that the collection efficiency for a specific size droplet is a function of the impaction velocity and the size and shape of the obstacles within its path. Trees present many size and shape elements to a droplet as it penetrates its envelope; consequently, the tree as a whole, possesses a collection efficiency based on the sum of all these small collection efficiencies for each droplet size. Indeed this may vary with fall angle depending on the orientation of the branch structure for various tree species. At this time, it is not feasible to model each of these effects and integrate them into a viable whole.

In the present study, the collection efficiency for individual droplet sizes was used as a fitting parameter to make the model conform to field data. In this way, the overall efficiency of the tree envelopes was established.

In addition to the predictions of the net penetration ratio to droplet size at ground level which was used in the comparison of data and model, the model output also provides percentage of spray droplets depositing above a given level in the canopy as a function of particle size.

For additional details of the model, the reader is referred to a report by Grim and Barry (1975).

RESULTS

A series of 16 computer runs was made with the model to illustrate how variations in each of the input parameters affect the penetration ratio as a function of particle size. Results are reported (Grim, Barry 1975).

It was interesting to note that there tends to be a built-in compensation for windspeed in the sense that an open stand of trees with light foliage would tend to have higher windspeed throughout the canopy, and this in turn causes a less steep trajectory of the droplets, thus giving a higher probability of capture, whereas a dense forest, with low wind speeds within the canopy, lessens the capture probability at all points except the uppermost portion of the canopy. This effect would probably be heightened by increasing the capture efficiency with impaction velocity.

In addition to the predictions of the penetration ratio to particle size, at ground level, the model output also provides percentage of spray droplets depositing above a given level in the canopy as a function of particle size. This is illustrated in figure 2. There is no significant difference in the collection of 50 µm and 100 µm droplets for this set of forest and meteorological parameters, whereas a considerable difference exists for 200 µm and 400 µm droplets.

Another series of 12 model simulations were made to compare model predictions to observed data for spray penetration as a function of drop size. Computer input consisted of actual site parameters and conditions, existing at spray time. The results, which are presented in detail by Grim, Barry (1975) are relatively comparable to the observed data. Figures 3 and 4 are examples of these comparisons, one Zectran trial and one B.t. trial respectively.

CONCLUSIONS

A new mathematical model which uses physical characteristics of the spray, wind speed, and basic forest characteristics as input has been developed to predict spray deposition within the forest as a function of droplet size. The behavior of the model output is relatively consistent with the observed data from a series of 12 field trials. The trials, however, were conducted over a relatively limited range of meteorological conditions and forest types. Data generated by these simulations can be of practical importance to the aerial applicator in deciding upon spray strategy and selecting spray equipment for a given set of atmospheric and biological conditions. The first step in the use of these simulations would be a clear definition of the target. Questions to be answered are type of target (leaf or insect), target size, target location (top of tree, midcrown, branch, type, etc.). With an understanding of the target, simulations can be used in planning forest spray operations.

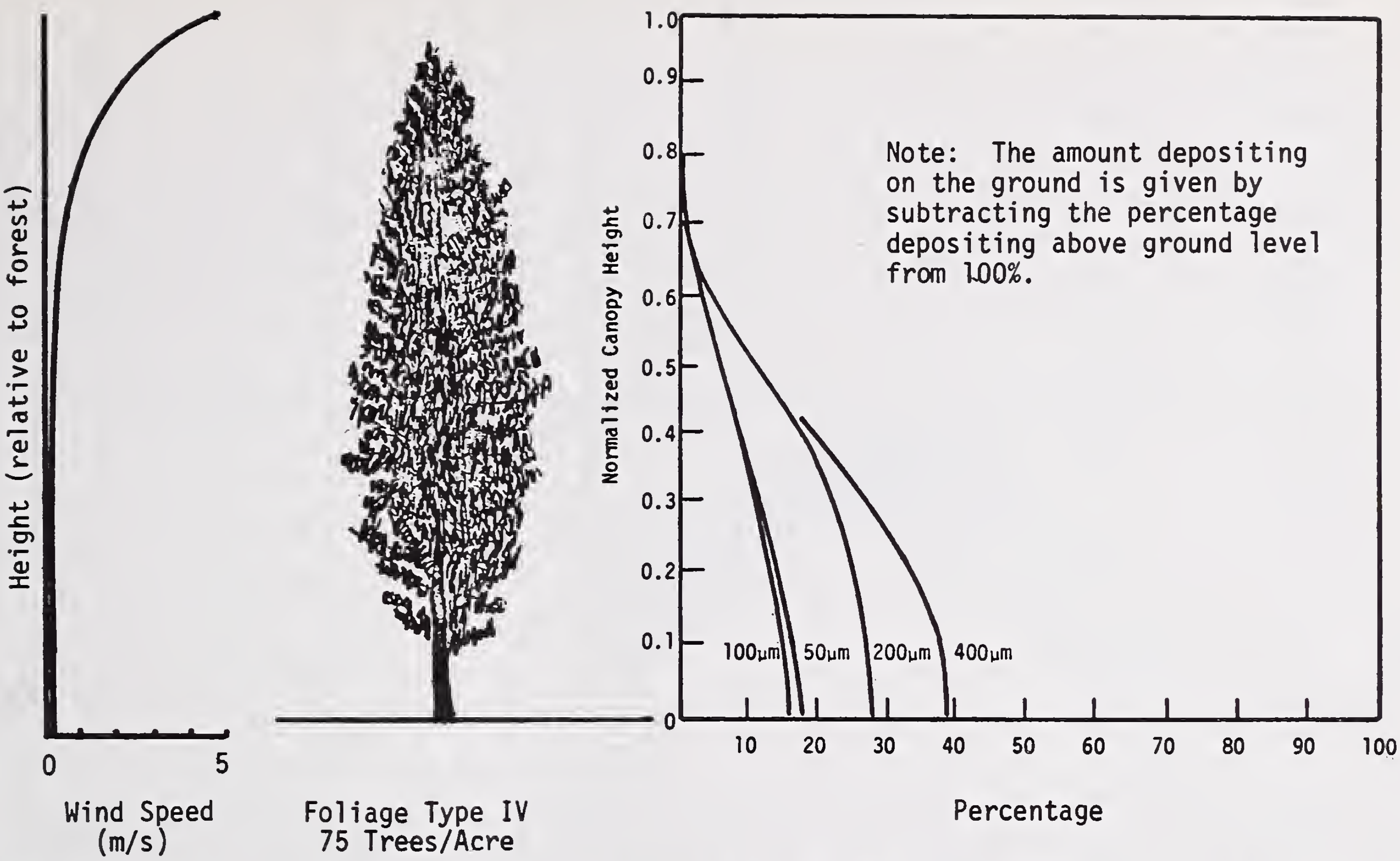

Figure 2.--Percentage of spray depositing above a given level in the canopy for the specified droplet sizes for type IV forest with a density of 75 trees per acre and wind speed of 2 meters per second.

Depending upon the droplet spray distribution and the collection efficiency of the insect, a large portion of the spray mass may, in effect, be wasted by being deposited at the top of the canopy, on the forest floor or lost by drift. The objective, of course, is to make the most effective use of the spray mass by generating droplets which have a high probability of coming in contact and impacting upon the target.

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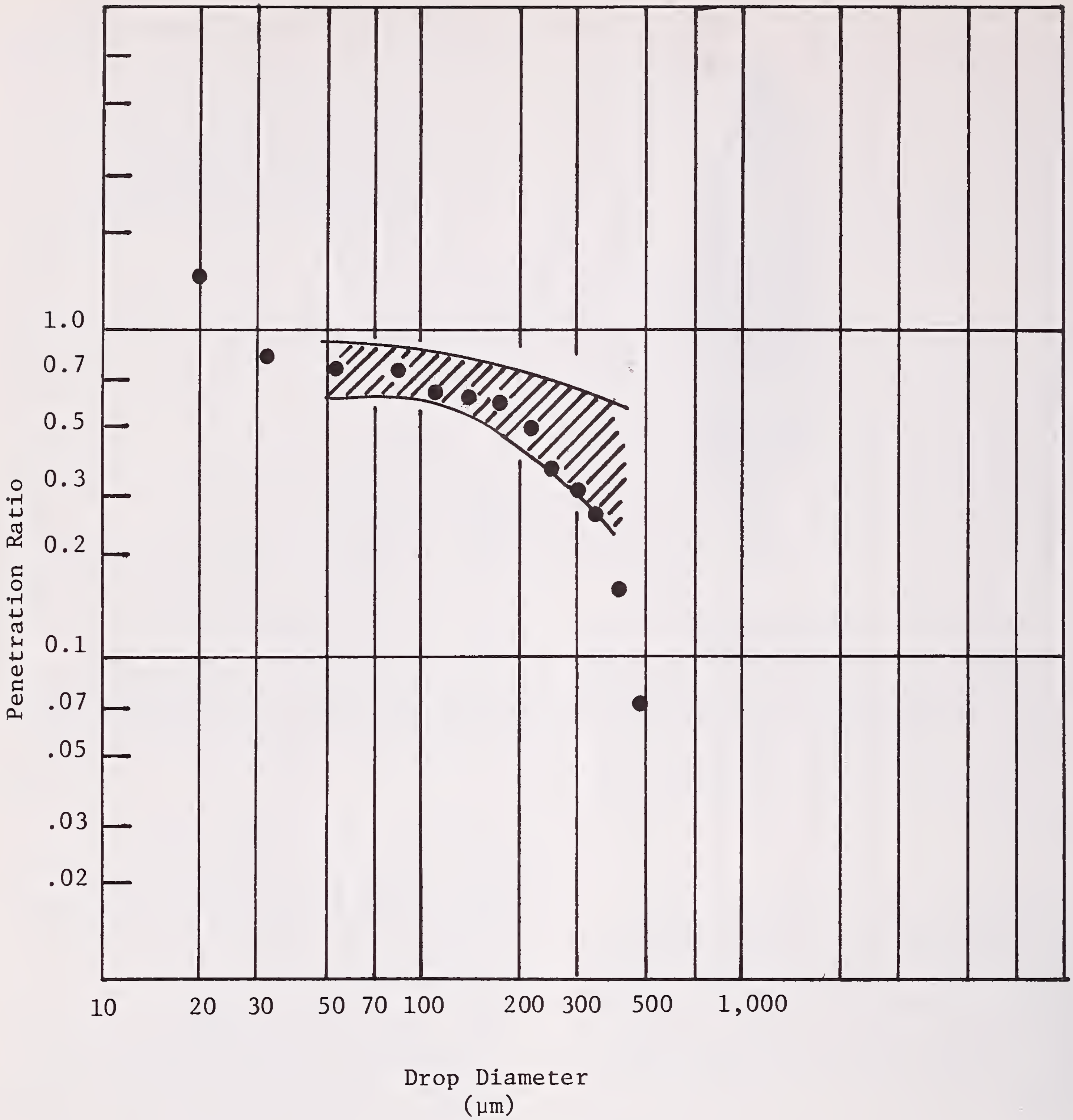

Figure 3.--Zectran trial 3 plot of penetration ratio to drop diameter comparing modeled (cross hatched) to observed (circles) data. Input included wind speed 0.94 m/sec and 50-100 trees per acre.

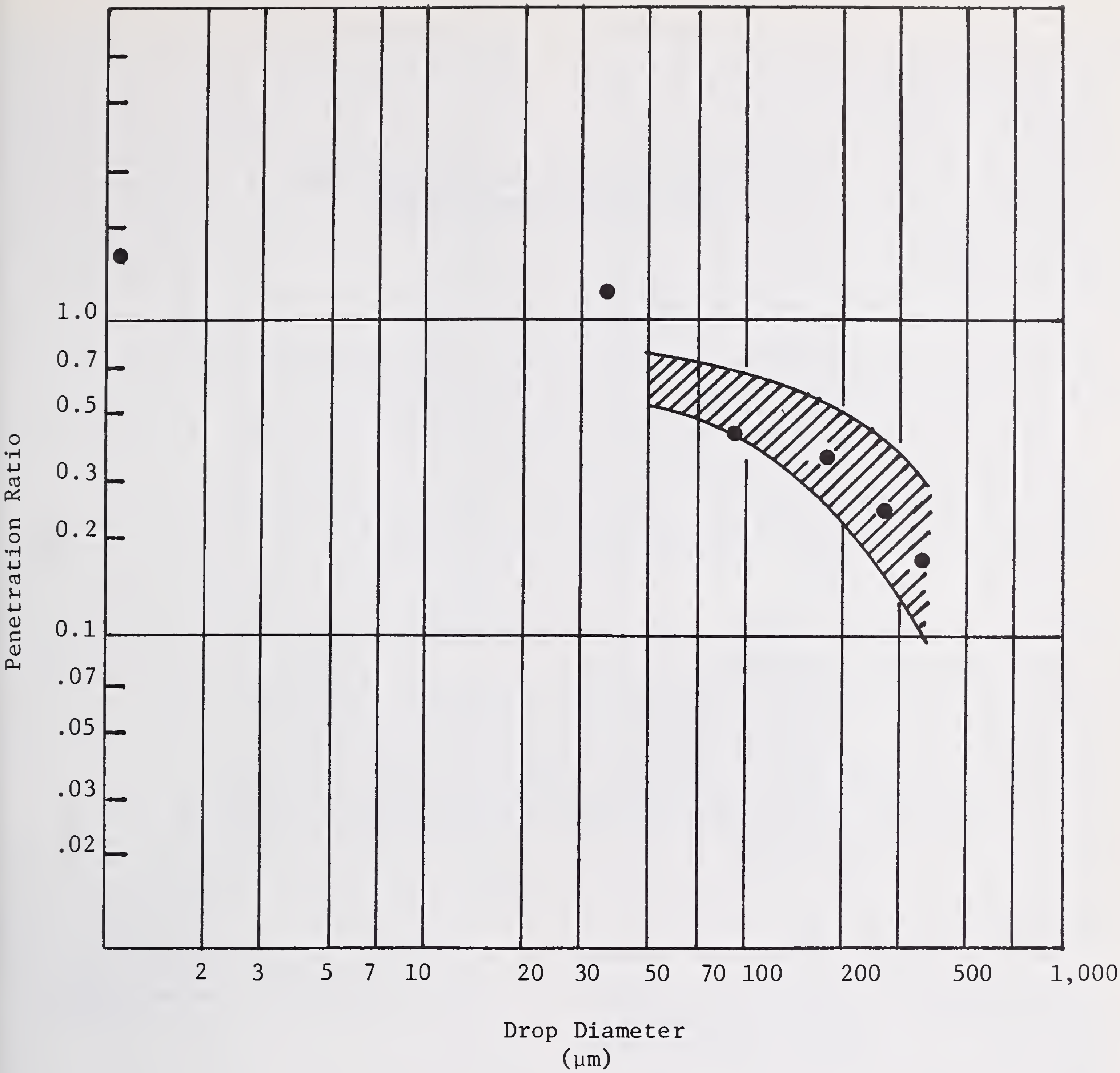

Figure 4.--B.t. trial 4 plot of penetration ratio to drop diameter comparing modeled (cross hatched) to observed (circles)data. Input included wind speed 1.0 m/sec., 25-75 trees per acre in the upper canopy and 175-250 in the lower canopy.

Some Measurements of the Adiabatic Wind Profile Over a Tall and Irregular Forest[1]

James D. Bergen[2]

Abstract.--Vertical profiles of windspeed were measured over a Douglas-fir stand on a level, exposed mountain site. The stand consisted of scattered old trees left after a harvest ranging up to 30 m in height, and younger trees up to 18 m tall. The average level of maximum foliage concentration was estimated at 14 to 16 m.

Windspeed profiles taken during neutral conditions were used to estimate the aerodynamic roughness length Zo and the displacement thickness D, using a least squares fit to the displaced logarithmic velocity profile relation.

The results for three ranges of above-canopy speeds indicate:

(1) an increase of roughness with speed;
(2) a general decrease in the displacement thickness with speed; and
(3) correspondence of the displacement thickness with the level of maximum foliage concentration, for high and moderate speeds.

The ratio of Zo at high and moderate speeds for the experimental stand to that found for a shorter, more uniform pine stand is approximately equal to the estimated ratios of the standard deviation of the foliage distribution approximated by a normal distribution above the level of maximum foliage concentration.

INTRODUCTION

When the effect of thermal stratification can be neglected the variation of windspeed with height Z over extensive stretches of tall vegetation has been commonly expressed in terms of the "displaced law of the wall". This relation is generally written as:

$$U = \frac{U_*}{k} \ln\left(\frac{z - D}{Zo}\right) \qquad (1)$$

where

U ≡ the local speed at height Z,
D ≡ the "displacement thickness",
Zo ≡ the "roughness length", and
k ≡ the von Karman constant
U_* is usually assumed to be the "friction velocity" defined independently by

$$U_* = (\tau/\rho)^{\frac{1}{2}} \qquad (2)$$

where ρ is the local air density, and
τ is the horizontal shear stress over the vegetative layer.

There is some ambiguity in the literature about the terms displacement thickness or height and the roughness length. Some authors replace D in relation (1) above by D' - Zo where D' is called the "displacement height"; (e.g. Kung 1961). A less common modification is to replace U by a velocity deficit U - Uo. In the first case the relation is unchanged insofar as neither D or D' is independently defined; in the second, if Uo is assumed proportional to U_* the corresponding term is absorbed in the constant Zo which also has no independent definition.

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[1]/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, Nov. 16-18, 1976.

[2]/ Research Meteorologist, Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Fort Collins, Colorado.

There is little theoretical basis for relation (1), and the validity of relation (2) for U_* estimated by the least squares fit of relation (1) to velocity profiles over a forest has never been established. In a wind tunnel simulation of flow over a forest canopy (Kawatani and Sadeh 1971) the value of U_* so inferred was found to be less than half that estimated from direct measurements of the turbulent velocity fluctuations. Although this question (the validity of this estimate of U_*) is obviously critical to the use of the "aerodynamic" method of estimating vertical fluxes over forest canopies, it lies beyond the data to be discussed in this report, which allow no independent estimate of U_*.

Considerable attention has been directed to the questions of how Zo and D vary with ambient speed over a given canopy, and how they are related to the physical structure of the forest.

For observations made over pine stands, it appears that Zo increases with increasing speed over the canopy, while D decreases although at a much lower rate (Valendik, 1968; Rauner, 1960). However, the degree of the variation differs markedly between stands. Even-aged, uniform stands show little or no systematic variation with speed over a considerable range of speeds (Allen 1968, Bergen 1971, Leonard and Federer 1973, Raynor 1971, Oliver 1971). More irregular stands show a stronger variation (Rauner 1960, Valendik 1968).

The correlation of Zo and D with stand characteristics has for the most part amounted to expressing both parameters as fractions of the average tree height -- a parameter which, as shown by Kawatani and Sadeh (1971), should not have any direct relation to either Zo or D. What agreement has been found between these ratios for different studies is probably due to a tendency for the experimental stands to be even-aged and in the vicinity of 10 m tall.

For such stands, the observed values for D are very close to the height D_f, for which the maximum amount of foliage can be found; a level for which minimum canopy speeds also occur (Bergen 1971, Kinerson and Fritschen 1971). Such a level may be a level of vanishing vertical shear stress -- an average separation surface for the canopy flow analogous to that produced by corners on objects placed in a normal boundary layer. For a quantitative treatment on the changes in such a level with above-canopy speed, we would need an expression for the local effective viscosity or at least some basis for estimating the vertical divergence of the shear stress at this level. Such expressions are, in general, still to be found. If we may argue by analogy with the separation patterns near corners in the wind tunnel, however, the more clearly defined the canopy foliage maximum the less variation would be expected in D with above-canopy speed.

If the total effect of the canopy upon the ambient flow may be regarded as the sum of individual shoot wakes, as seems plausible for pine and fir stands (Bergen 1975), the value of Zo should depend upon the vertical distribution of such shoots above the level D_f. The normal weight of needles per unit length of shoot is relatively constant for a particular species (Gary 1976) and for individual pine crowns, the distribution of foliage weight along the live crown roughly approximates a Gaussian distribution, with a standard deviation of about 1/5th the total live length (Stephans 1969). For a nonuniform but random canopy the summation of such crowns would also approach a Gaussian distribution, with a standard deviation σ depending upon the rms value of the live crown length weighted by total crown foliage mass. If we may neglect the shear stress at D_f, and if we can assume that the drag coefficients C_B for individual branches are constant over the range of speeds from D to the top of the canopy, then elementary physical reasoning argues that

$$Zo = \sigma f(A, C_B) \qquad (3)$$

where A is the leaf area index of the stand. The amount of foliage surface per unit length of needle-bearing branch is assumed invariant through the canopy and the same for stands to be compared.

The function $f(A, C_B)$ would be nonlinear only if near-wake interaction were considered, but this is excluded by the hypothesis:

$$Zo \propto \sigma A \, C_B \qquad (4)$$

It should be noted that (4) would apply only in the narrow range of U_* where the canopy speeds at all levels above D yield the same value of C_B. Wind-tunnel studies of C_B are not reassuring in this regard. They show a very narrow interval in the 1 to 2 mps range where C_B is essentially constant.

TEST SITE

The measurements to be discussed were made at a relatively level site at 2500 m elevation near Cle Elum, Washington. The forest consisted of an uneven-aged mixture of Douglas-fir and larch, with the former predominating. An edge view is shown in figure (1). The distribution was the result of selective cutting some decades earlier which resulted in a widely scattered group of older trees with heights ranging from 20 to 30 m, and newer growth, more uniformly distributed, with heights up to about 18 m.

In addition to the high variation in tree height, the stand contained many glades several tree heights in diameter.

Figure 1.--The experimental stand, viewed from an edge downwind from the tower site.

Figure 2.--The anemometers were arrayed on a 37 m crank-up tower.

The stand floor was extremely rough, with layers of wind-thrown trees and logging slash.

MEASUREMENTS

Gill three-component propeller anemometers were used for the wind profile measurements. They were mounted on 1-m arms clamped to the lattice work of a 37-m crank-up tower (fig. 2). The instruments had a clear fetch for southwesterly through north and to easterly winds in regard to the tower frame. Wind speeds were measured at 3720, 3540, 3350, 3170, 2900, and 3810 cm above the forest floor.

The same instrument arms supported aspirated and shielded bead thermister thermometers at each level.

Windspeed components were measured at 1-minute intervals together with temperature outputs.

The tower was leveled after instrument placement by means of plumb lines extending from the tower top. Five-minute average vertical velocities at the tower top were less than 5 percent of the total windspeed, which would appear to argue that both tower tilt and local divergence of the flow were slight.

The measurements to be discussed were made from morning to late afternoon on four days. Cloud cover was appreciable for only a few hours of the record.

Anemometer threshold velocity was approximately 25 cm/sec (cmps).

STAND SURVEY AND FOLIAGE DISTRIBUTION ESTIMATES

Tree characteristics were sampled by reference to a rectangular grid laid out in the vicinity of the tower. For each of about 20 grid points, the nearest tree was selected for each point of the compass. Trees less than 4 m tall were neglected. In addition, the characteristics of the tallest tree within about 30 m of the grid point were measured.

Foliage characteristics were estimated from diameter at breast height, total height, and the height to the live crown by means of the regression model for Douglas-fir crown structure developed by Kinerson and Fritschen (1971). The estimated distribution of foliage weight for the stand is shown in figure 3. The total leaf area index is about 5, considerably less than for the more uniform stands for which most published wind profile data apply.

The maximum foliage concentration for the stand as a whole is at about 15 m. The dominant trees as a separate group do not show a clear maximum, but highest values apparently are at about 20 m height. When only the newer growth is considered, the maximum foliage is concen-

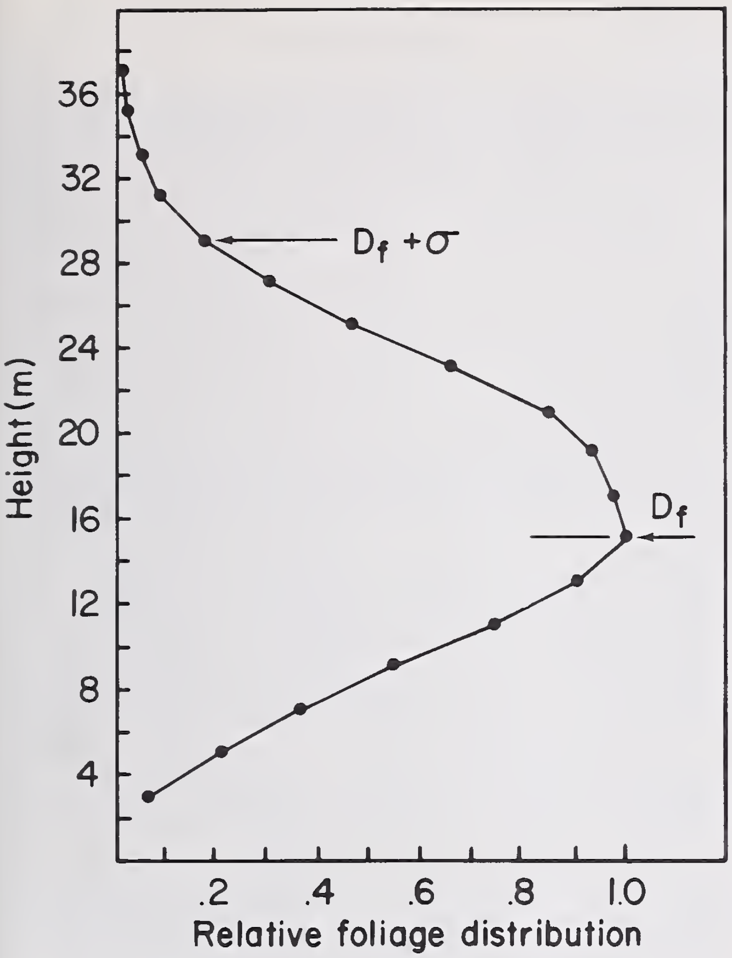

Figure 3.--Average foliage distribution with height for the experimental stand.

trated at 9 m.

The average tree characteristics on the site were: height, 17.1 m with a specific variance of 48 percent; and diameter at breast height (dbh) of 26 cm and 54 percent. Average stem density corresponds to about 256 m^2 per stem since average spacing between trees as measured between the four trees selected at each sampling point was about 16 m.

ANALYSIS OF DATA

Individual profiles were selected from the record for which the Richardson's number calculated from the windspeeds and temperatures at the top and lowest levels of the profile array were between -0.2 and +0.2. The sample was further stratified by the windspeed at the 38 m level into classes of 200 to 400 cmps, 400 to 600 cmps, and above 600 cmps. These will be referred to as the low, moderate, and high speed categories, respectively.

The speeds for each profile were scaled by the speed at the top of the array and assembled as an average for each of the three classes. With this scaling, the relation to be fitted was of the form:

$$\frac{U}{U_h} = 1 + B \ln \left(\frac{z - D}{h - D}\right) \qquad (5)$$

where (h) is the height of the topmost anemometer (38 m), and where

$$B = \ln^{-1} \left(\frac{h - D}{Zo}\right)$$

The discussion of the previous section indicates that only positive values of D, h - D, and Zo are physically plausible. This constraint was incorporated into the least squares fit calculation by introducing the variables (α) and (β) where

$$D = H \sin^2 \alpha + bH$$
$$B = \beta^2 + c$$

The lower bounds for D and B are thus bH and c respectively, while the upper bound for D is (1 = b)H. The scale height H was taken as 28 m, b and c were finally set at 0.5 and 0.05 respectively. The criteria for the choice was that neither D nor B should be at its upper or lower bound at the final values for best least squares fit.

The algorithim used is essentially that published by Hickman (1966) under the program name DATFIT, which was designed for nonlinear curve-fitting problems. It should be noted that the question of the applicability of von Karman's constant in relation (1) above arises solely in the validity of relation (2) for the least squares estimate of U_*. In the foregoing procedure the problem is avoided for the determination of Zo and D.

RESULTS

The number of profiles in the low, moderate, and high speed classes were 35, 40, and 20 respectively. When the curve-fitting procedure described above was applied to the scaled profiles for each of the three classes, the last two fitted relation (7) with the associated constraints relatively well; correlation coefficients were about 0.98. For the first class, however, relation (7) gave a fit not significantly better than a linear variation for positive values of D; the measured wind shear was greatly in excess of that appropriate to relation (7). The profiles in the nearest unstable class at the same speed range, however, gave an acceptable fit to relation (7) with a correlation of 0.98.

The precision of the above-canopy temperature measurements ($\pm$ 0.1°C) was marginal given the slight gradients existing over the canopy even with relatively strong insolation. Since

Table 1. Tower-top wind speeds and directions, and temperature drop from 28 to 37 m for speed class profiles

Speed class	Wind speed			Wind direction		Tower temperature drop		
	Average	Maximum	Minimum	Degree from North	Range	Average	Maximum	Minimum
		cm/sec		*Degrees*			C^o	
Low	282	378	216	77	46	-.50	-.06	-.55
Moderate	521	600	405	79	5	+.32	+1.1	-.17
High	771	1000	601	103	11	+.12	+2.3	-.50

the wind speed variation is probably a better index to stability than the measured temperature gradient under low speed conditions, the estimates of Zo and D for the low speed class were made from the 13 profiles in the slightly unstable class. Table 1 lists the averages and extremes for tower-top wind speeds and directions, and the temperature drop across the tower array for each of the speed classes.

The values for D for the low, moderate, and high speed classes are 16.8, 14.7, and 16.0 m respectively. The associated roughness heights were 165, 286, and 251 cm. Since errors in the D estimates tend to be associated with errors of the opposite sense in Zo, resulting in the relative constancy of D + Zo noted by Valendik (1968), the observed variation suggests a decrease in D with speed and an increase in Zo. We may say with more certainty that the drag coefficient rises substantially from the lowest speed class to the moderate and high speed classes. It is about the same for the last two classes: approximately 0.14 at 28 m, compared to 0.09 for the low speeds. It would appear that, in the range of constant drag coefficients considered in the argument for relation (4), D corresponds well with the level of maximum foliage concentration for the stand as a whole, 15 to 16 m.

The scaled profiles for each of the speed classes, together with the fitted curves for relation (7), are given in figure 4.

The values of D are of the same order of magnitude -- 16.4 m -- as those calculated by Kung (1961) from Gisborne's measurements over a 24 m tall mixed conifer stand at tree top speeds of about 160 cps, but the estimated roughness length is far smaller -- 250 cm as compared with 1347 cm.

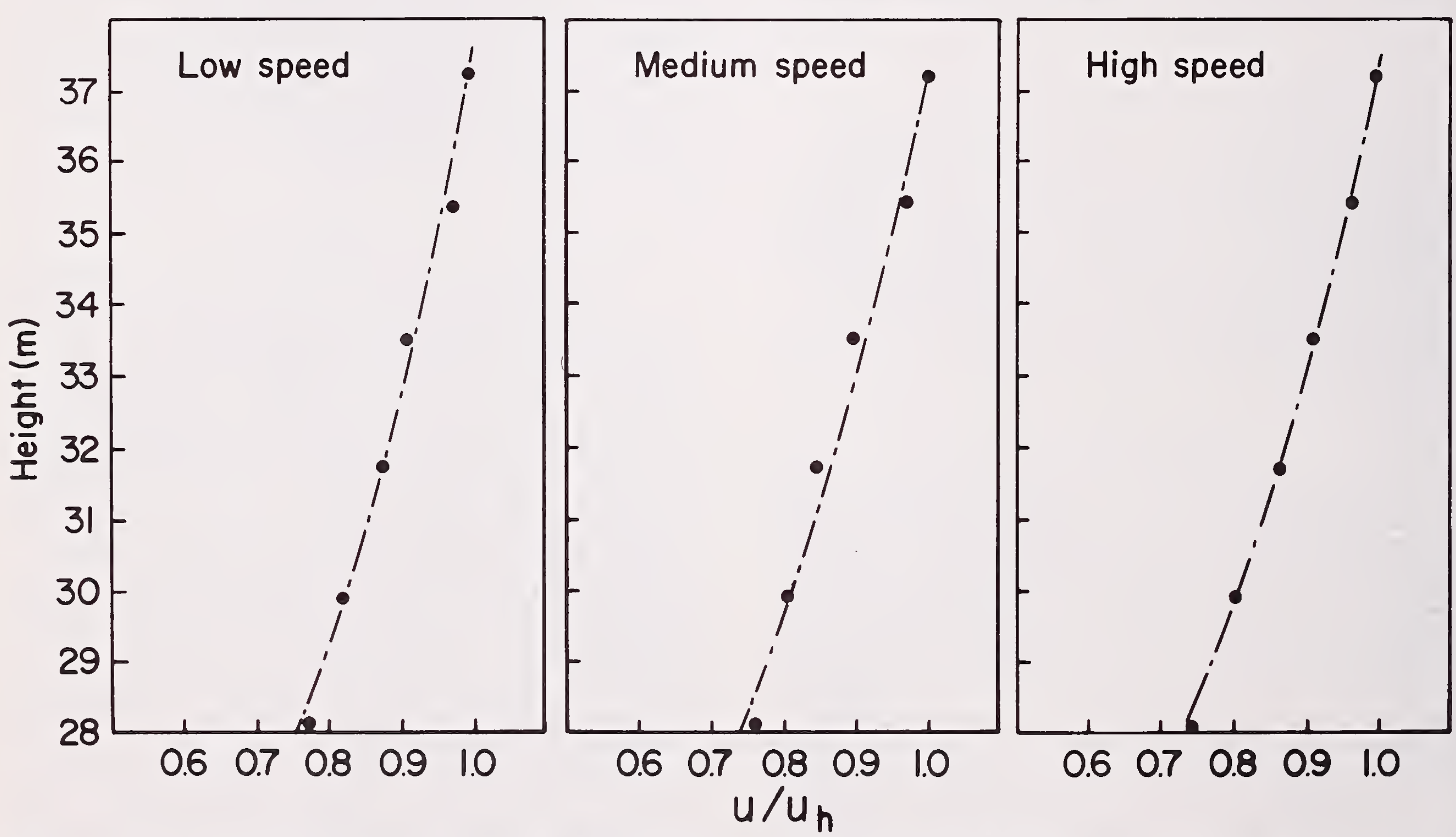

Figure 4.--Scaled wind speed profile, speed groups with estimated displaced logarithmic profiles.

CONCLUSIONS

The results indicate that the close association of D with the foliage maximum observed for more uniform stands is also evident for the heterogenous situation where the foliage maximum is the resultant of many differing individual crowns.

The ratio of D to the average tree height is 0.88, larger than observed for shorter stands (e.g., Oliver 1971). If the maximum tree height is considered, the ratio falls to less than 0.5. The relation of the maximum foliage height to the average tree height is a silvicultural consideration but it would appear that the former is the better predictor for D from forest inventory data.

Relation (4) can be tested in a comparison with results from a more uniform stand (Bergen 1971, 1975). The length (σ) as calculated from the vertical foliage distribution for a 10 m tall even-aged lodgepole pine stand (Gary 1976) is about 200 cm. The leaf area index was approximately 8. The estimated value of Zo was 50 cm. With (σ) equal to 1400 cm and leaf area index equal to 5, relation (4) would predict a Zo of 220 cm, about 4.3 times the previous value,for the Douglas-fir stand. This is a reasonable approximation, considering the difference in species and thus C_B as well as the errors involved in the foliage estimates for the Douglas-fir stand.

The results seem to indicate that relation (1) may be useful for routine forestry applications involving air flow over forest stands insofar as it may be possible to predict Zo and D with reasonable accuracy from inventory data, once the variations of C_B are known in more detail.

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First Results on a Differential Interception Method of Estimating Canopy Dosage from Aerial Pesticide Applications[1]

James D. Bergen and Richard A. Waite[2]

Abstract.--Current methods for assessing aerial pesticide applications do not allow an estimate of the actual pesticide dosage as predicted by available models for spray penetration into the forest canopy, or provide the information required to estimate deposition on the various foliage elements. Field experiments are reported on spray deposit measurements using cylinder pairs exposed in a forest canopy The relative deposition of droplets in 8 to 52 μ size range on a 2.5-cm cylinder and a 6-cm cylinder is used to estimate the effective ventilation speed for the cylinder deposits, which may then be used to estimate the corresponding dosage for droplets in that size range.

The nonuniformity of the deposit requires intensive sampling. The effect of local turbulence is evident in the deviation of the deposit pattern over the cylinders from that predicted from theoretical considerations.

INTRODUCTION

Although aerial spraying of pesticides into forest canopies has become commonplace, increased awareness of the hazards involved requires that we minimize the undesirable side effects of massive applications of such agents. As a result, there is a need for greater precision in the assessment and design of forest spray operations. While the conventional ground-deposit-card method of estimating the total amount of material applied to the foliage works well for large droplet sizes, it fails to account for that portion of the material in droplets below 100 μ in diameter, and gives little information on the vertical distribution of the spray deposit within the canopy.

While direct measurement of foliage deposition would give the best estimate of the deposit distribution as well as an indication of the drift loss, in practice this is a difficult and time-consuming procedure. The obvious alternative is to correlate deposition measurements on cards placed in one way or another near or in the foliage with deposition on the foliage surfaces. This correlation should be a function of three parameters: the drag coefficient of the foliage element, the local windspeed during the passage of the spray droplets, and the time (t) integral of the volume concentration (n) of droplets of a given size during the spray application, termed the "dosage", (N):

$$N = \int_0^\infty n\,dt$$

The lateral drift of small droplets would be directly expressed as the product of the dosage and the average windspeed.

As a matter of convenience, deposition cards mounted on cylindrical forms of various sizes have been routinely used for such measurments.

The ability of cylinders to intercept horizontally moving droplets of a particular diameter (d), and density (ρ) at a given,

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steady windspeed (U) is formally expressed as the "collection efficiency"(E). The efficiency is defined as the ratio of the number of droplets impacted on the cylinder (C_i) to the number of droplets contained in the volume of the aerosol cloud swept by the clinder:

$$C_i = E\,U\,N\,D\,L \qquad (1)$$

where (D) is the cylinder diameter, and (L) its length.

Values of (E) have been calculated for particular droplet-cylinder combinations by a number of authors (Langmuir and Blodgett 1943, Lundberg and Chilton 1962) and have been widely used in such problems as wire icing estimates and filter design. These calculations show reasonable agreements with small droplets ($d < 100\,\mu$) in wind-tunnel situations, but do involve some critical assumptions relevant to more complex ambient air flows:

(1) The droplets are assumed to be moving at the local airspeed up wind from the cylinder, an improbable situation for a spray droplet larger than about 100 μ falling through a typical boundary layer flow.
(2) The air flow is assumed to be steady, a condition rarely found in natural boundary layers.
(3) The air flow is assumed to be perpendicular to the cylinder axis.

Given these assumptions, (E) may be shown to depend upon two dimensionless numbers, (K) the "inertial parameter" defined as

$$K = \frac{1}{9\mu}\,\frac{d^2 U \rho}{D} \qquad (2)$$

and a parameter (ϕ) where

$$\phi = \frac{9\,\rho_a^2\,D\,U}{\mu\,\rho} \qquad (3)$$

where ρ_a and μ are the density and viscosity of the air.

The speed (U) which enters into definitions (2) and (3) is the magnitude of the wind component normal to the cylinder axis. The function $E = f(\phi, K)$ to be used in the following discussion is that calculated by Langmuir and Blodgett (1943) and presented as a convenient nomograph in the Air Weather Service Climatic Methods File (U.S. Air Force 1960). The velocity field for these calculations corresponds to potential flow around the cylinder.

The deposition to be expected without impaction -- that is, in still air -- (C_s) is

$$C_s = V_T\,N\,D\,L \qquad (4)$$

where (V_T) is the terminal velocity of the droplets, about 1.9 and 6 cm/sec for 24 μ and 41 μ diameter droplets, respectively.

Strictly speaking, (C_s) and (C_i) may not be superimposed. The response of droplets to the local air motion depends upon their total speed relative to the surrounding air for droplets larger than a few microns. A falling droplet would act as a droplet of lower mass in regard to its impaction on a local surface. The available calculations do not consider the coupling of the sedimentation velocity and the horizontal motions, and for the following discussion this effect will be assumed negligible. With this assumption the total deposition or catch (C_T) on the cylinder may be written

$$C_T = NDL\,(E\,U + V_T) \qquad (5)$$

The deposition density (c), is equal to (C_T/DLN). Some calculated values of c for oil droplets of diameters 24 μ and 41 μ are given in fig. 1. The calculations are made for two cylinder diameters, 6.5 and 1.25 cm, labeled (L) and (S) respectively, and plotted against the ventilation speed (U). Ambient conditions of 25°C and sea level pressure are assumed.

At speeds below 20 cm/sec the deposition is dominated by sedimentation.

Where (U) is known, the measured depositions of droplets as measured around sample chord strips of the cylinder card could be used via relation (5) and the curves of fig. 1 to calculate (N) for 24 μ or 41 μ droplets.

Accurate measurement of the local wind speed is not practical within the forest canopy. Both wind direction and speed are random functions of position and time. The measurements described in this paper are part of an exploratory effort to determine the local effective windspeed (U) in such a situation by the use of cylinder pairs.

If we consider the two cylinders close enough as to experience no systematic difference in local values of (N) at a particular time, we may define a relative catch density deficit (RCD) by

$$RCD = \frac{c_a - c_b}{c_a + c_b} \qquad (5)$$

where the subscript (a) denotes the smaller cylinder and (b) the larger.

By substitution:

$$RCD = \frac{(E_a - E_b)\,U}{(E_a U + E_b U + 2V_T)}$$

and the RCD for a particular droplet size will depend only on the local speed.

The variation of RCD with (U) is shown in fig. 2 for the two droplet and cylinder sizes considered above. These values will be taken as representative of droplets in the 8 to 30 μ range and the 30 to 52 μ range in the discussion below.

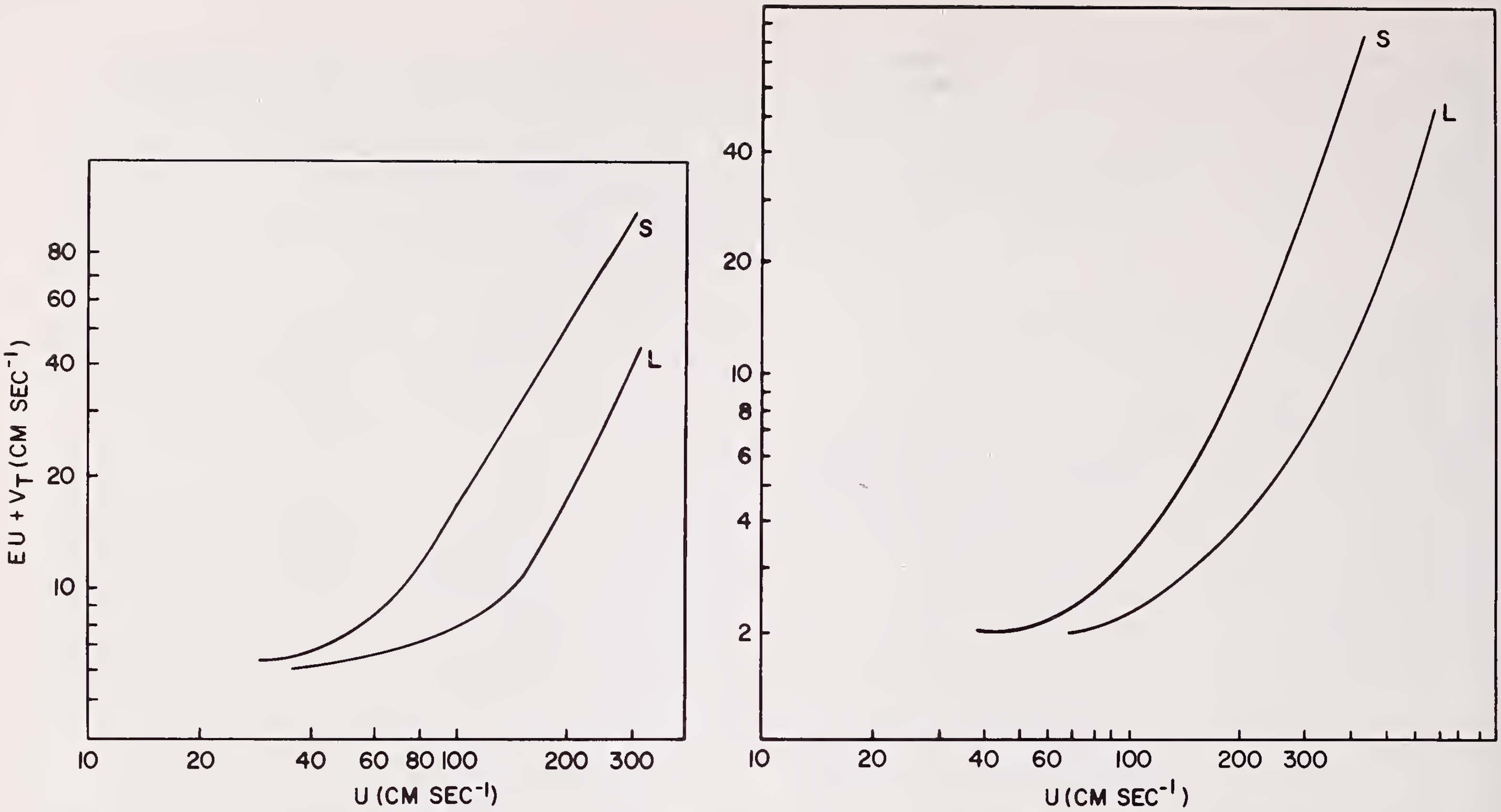

Figure 1.--Variation of deposition velocity with ventilation speed for (A) 41 μ diameter oil droplets, and (B) 24 μ diameter oil droplets. L = large cylinder, S = small cylinder.

Since canopy windspeeds are generally in the range from 50 to 200 cm/sec during aerial spray applications, the curves of fig. 2 suggest a means of estimating the local ventilation speed from the relative catches on such cylinders in the 41 and 24 μ droplet diameter ranges.

A typical measurement (as noted below) resulted in a stain droplet density of 11.3 cm^{-2} on the small cylinder and 3.7 cm^{-2} on the large cylinder, for stain diameters corresponding to the 24 μ droplet range. The corresponding densities for the 41 μ range were 8.2 and 1.5 cm^{-2} respectively. The calculated RCD for the smaller droplets was thus about 0.5, a value which could by the curve of fig. 2 occur with speeds of 240 or 700 cm/sec. The corresponding RCD's in the 41 μ range would be 0.65 or less than 0.1 as compared to the calculated value of about 0.7. Our estimated speed is thus about 240 cm/sec. If we turn to the deposition velocity ($EU + V_T$) curve of fig. 1 we find a value of 18 cm sec^{-1} for the small cylinder and 5.3 cm sec^{-1} for the large cylinder. Returning to the measured stain densities and applying equation (5) we find estimated dosages in the 24 μ range of 0.63 and 0.7 droplet cm^{-3} for the small and large cylinder separately with a mean of about 0.66 droplet cm^{-3}. The same calculation may be carried out for the 41 μ droplets.

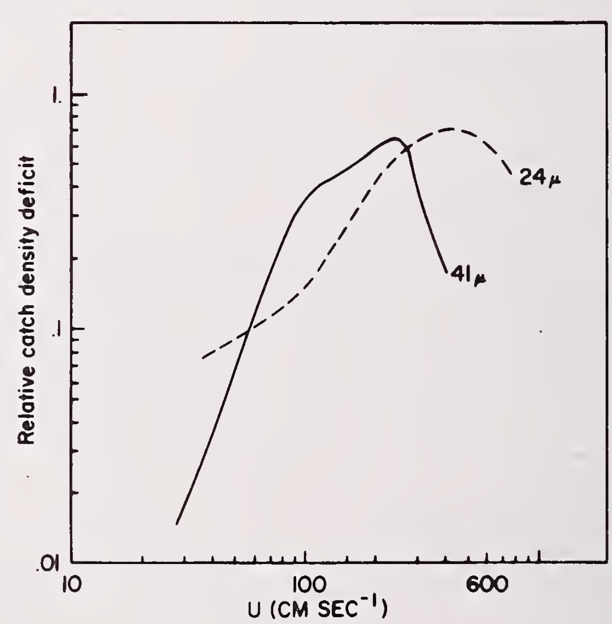

Figure 2.--Variation of RCD with ventilation speed for two droplet sizes.

IMPACTER DESIGN

Unit cost is a critical factor in determining the density of sampling in spray assessments. The ready availability of empty beer cans at a nominal cost as well as their light weight suggested their selection for one of the cylinder sizes. The use of styrofoam dowel for the smaller cylinder eliminated the need for relatively expensive cutting and drilling required for wooden dowels.

Figure 3 is a schematic of the impacter design used, with the two cylinders mounted coaxially and horizontally on a standard wire coat hanger.

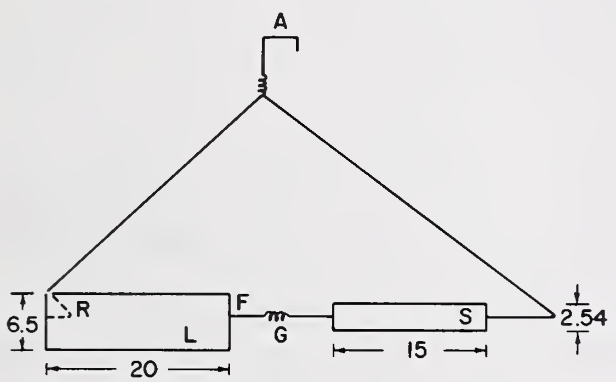

Figure 3.--Schematic of deposition cylinder pair. Beer can (L) is held in position by the bent corner of the coat hanger inserted in tab opening at (R). Wire is reconnected at (G). Frame is held to a line by a spring paper clip at (A). Styrofoam cylinder (S) is impaled on lower coat hanger bar. All measurements are given in centimeters.

In the field situation to be discussed, the coat hanger top (A) was clamped to a taut nylon line suspended from a pulley hung between trees. Khrome coat cards were fastened completely around the normal circumference (the chord) of the cylinders with rubber bands.

A horizontal cylinder arrangement, rather than vertical as suggested by Reid (1965), allowed the total deposition -- including the larger drops which show negligible horizontal motions at low windspeeds -- to be measured with the same deposition cards. The horizontal arrangement also simplified the sampling problems involved in estimating the catch. If the air flow is primarily horizontal, the maximum impaction deposition remains at the cylinder midline, even for multiple depositions made with reasonable variations in horizontal wind directions. The midline density therefore reflects the average speed and concentration as distinguished from the multiple discrete maxima that would be observed with vertical cylinders in the same situation.

SAMPLING

The collection efficiencies on which the curves of fig. 1 are based refer to the entire chord of the cylinder, and strictly speaking provide only estimates of total chord accumulations or average stain densities.

The safest procedure would be to survey the entire chord as suggested by Reid (1965), but this is time consuming and expensive, even using electronic scanners such as the Quantimat 3. It would therefore be of advantage to develop a sampling system that would allow a quicker estimate of total chord concentration.

The total accumulation of droplets on the cylinder chord consists of two contributions: (C_i) the impact deposit, and (C_s) the sedimentation deposit. Their variation over the chord should be quite different.

By geometrical consideration, (C_s) should vary as ($\sin \gamma$) over the upper chord where (γ) is the angle from the horizontal and thus, approximately, from the midline stain maximum if such can be determined. On the lower chord (C_s) should be uniformly zero. There should be no effect of either windspeed, droplet size, or cylinder size on the (C_s) distribution.

The (C_i) deposit by contrast is, for steady flow, confined to the section of chord between ($+\gamma m$) and ($-\gamma m$) where (γm) is termed the "critical angle" (Lundberg and Chilton 1962). The angle (γm) depends on (ϕ) and (K) above; it increases sharply with the latter. At a speed of 90 cm sec^{-1}, γm for the 41 μ droplets on the large cylinder is about 0.2 radian; for the small cylinder it would be 0.4 radian. At 180 cm sec^{-1}, γm for the cylinders increases to 0.25 radian and 0.8 radian, respectively. For the 24 μ droplets the variations are smaller but in the same sense.

Since devices such as the Quantimat are used with a fixed sample area, the midline sample would include a larger fraction of the impacted droplets at lower speeds and for the larger cylinders.

Since the (C_s) distribution does not vary with speed, the midline sample should contain a (C_s) deposit equal to a constant fraction of the deposition on the top of the cylinder.

From these considerations we would expect a double maximum pattern on a cylinder exposed to a reasonably steady flow; the magnitude of the midline maximum relative to the maximum at the top of the cylinder would increase with speed and be greater for the larger cylinder at the same speed. However if the scanning devices use a fixed sample area, the fraction of the impacted droplets included in this area would be larger for lower speeds and the larger cylinder.

For an upstream flow with considerable turbulence or for the net deposit caused by multiple cloud passages with differing speeds and/or directions, one would expect the inertial deposit to extend well beyond (γm) estimated from the speed (U) implied by the ratio of deposits at the midline.

MEASURED DISTRIBUTIONS

Sixteen cylinder pairs were exposed in a forest canopy during an aerial spray operation. They were hung within the canopy, as described above, at heights ranging from 4 to 25 m and at distances of 30 to 90 m downwind from the helicopter flight path. The application consisted of seven swaths laid down over the same path over a period of about 20 minutes.

Details on the canopy characteristics can be found in an earlier report (Bergen 1976). The spray consisted of Rhodium B dye in a diesel oil carrier. The experiment was carried out in the early morning, with above-canopy windspeeds varying from 150 to 250 cm/sec as measured by 5-minute averages at about 20 m over the tree tops.

The deposition cards were analyzed on Quantimat equipment using experimentally determined spread factors. Sampling areas for the scan were 0.98 cm^2. The cards were scanned at 1 or 2 cm intervals along the chord. Only cards with a midline deposit density of at least 6 drops per cm^2 were surveyed (15 cards). Chords were scanned at three locations along the cylinder axis.

The results for drops in the 24 μ and 41 μ ranges are shown in figures 4 and 5 as polar plots of droplet density expressed as a fraction of the average droplet density over the cylinder plotted against the angle from the apparent midline position as indicated by the deposition maximum. The plots are divided into high and low speed insofar as the 24 μ RCD for the pair indicated ventilation speeds less than or greater than 160 cm/sec.

Perhaps the most apparent feature of the plots, particularly for the more detailed beer can results, is the extreme irregularity of the deposits away from the very clear midline maximum. There is considerable deposition at the lee midline, where, for steady flow by the Langmuir-Blodgett model, there should be none -- a consequence presumably of either turbulent fluctuations in wind direction during droplet impingement, or of reverse flow in the cylinder wake. The beer can results show, as would be expected from the previous discussion, the two maxima for the independent distributions (C_s) and (C_i), with the former most prominant for the low speed data. For the higher speeds, the (C_s) maximum is submerged in the more widely distributed (C_i) pattern. The results for the small cylinder are more ambiguous, perhaps because of the lower angular resolution provided by the sean sample area. The relative decrease in (C_s) is obvious for the smaller drops, but less apparent for the 41 μ drops. For both speed classes the lee midline deposition is appreciable.

It appears the impaction deposit on the cylinders occurred to an appreciable extent with nonhorizontal winds, a conclusion that would cast considerable doubt on any simple sampling procedure using less than 5 points on the chord. Still, insofar as the turbulence characteristics of natural conifer stands resemble each other, an estimate of total deposit from midline samples does not appear to be entirely out of the question for the 24 and 41 μ droplets. The ratio of the midline deposit to total deposit varies little for the droplets -- about 15% and 14% for the small and large droplets on the beer can, and about 29% and 25% on the small cylinder. These ratios are particular, of course to the sampling area, the type of turbulence, and droplet size. These estimates would probably be of some validity in approximate estimates for cylinder pairs deployed in similar stands.

SIGNIFICANCE OF THE SPEED

The relation of (U) to the time average wind as generally defined with conventional measurements is not obvious. Physically we should expect (U) to approximate the rms value of the windspeed during the relatively short periods of time during which the spray cloud or clouds pass the collector. For a large enough number of swaths this rms value may approach that estimate from the usual 5-minute average; this in turn is generally defined in terms of the gust factor or turbulence intensity, the ratio of the standard deviation of the velocity to its average. For forest canopies turbulence intensities of 2 or 3 are not uncommon at lower speeds, so that (U) may exceed the mean speed by a factor of 3 or 4. Balancing this effect to some extent is the random orientation of the collector relative to the local wind direction; the average of a large number of such local estimates would be less than the true speed by a factor of 0.7.

In the sample calculation made above: if the cylinder were at right angles to the average wind direction a reasonable measure of the lateral drift would be the product of the estimated mean velocity which is about 80 cm/sec times the dosage, i.e. about 40 droplets cm^{-2}.

The correlation between the local dosage and wind speed and the final deposition on a typical foliage element has yet to be established. Calculations such as those carried out for solid, smooth cylinders to establish (E) have not

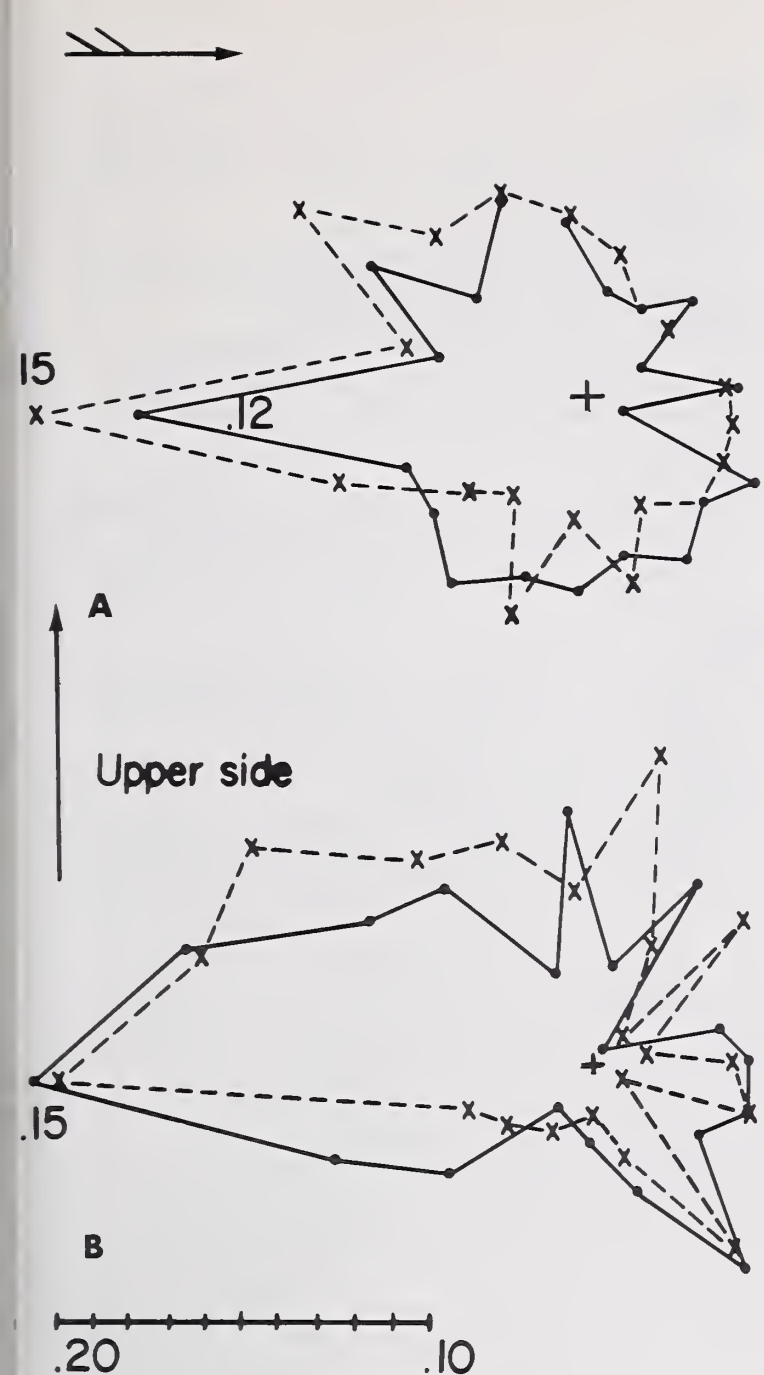

Figure 4.--Composite angular distribution of droplet stain density normalized to total catch. (A) Large cylinder at low speeds (130-160 cps); (B) Large cylinder at high speeds (160-240 cps). Scale represents magnitude of normalized stain density, + indicates center of cylinder, x = 41 μ, • = 24 μ.

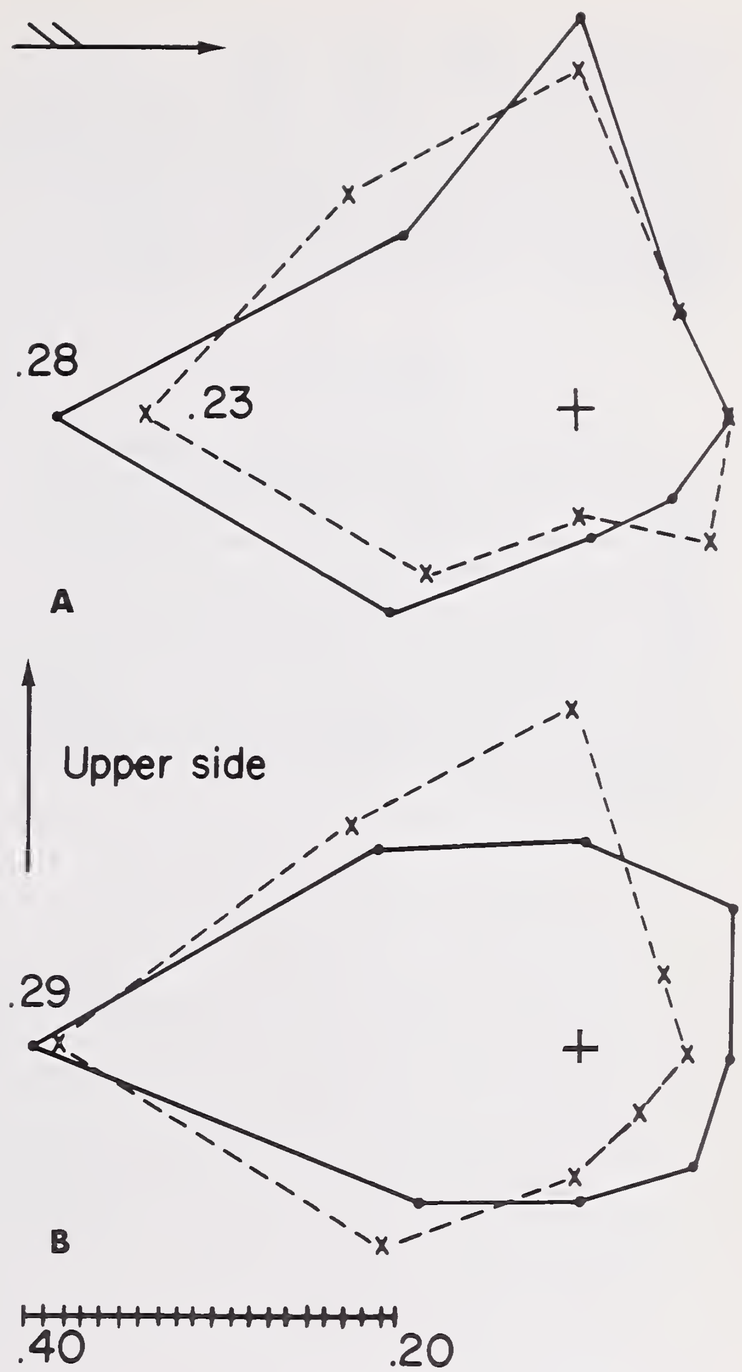

Figure 5.--Composite angular distribution of droplet stain density normalized to total catch. (A) Small cylinder at low speeds (130-160 cps); (B) Small cylinder at high speeds (160-240 cps). Scale represents magnitude of normalized stain density, + indicates center of cylinder, x = 41 μ, • = 24 μ.

been made for rough, porous bodies suspended in an air stream. Any available data on interception by branches or crowns refer to fog droplets with sizes in the 1 μ range. For such particles (Yosida and Kuraiwa 1953) the total interception appears to vary directly with (N), the total projected leaf area, and ($U^{3/2}$). It seems obvious that further study on this point is called for.

CONCLUSIONS

The double cylinder method appears to offer a practical way of measuring dosage and estimating lateral drift in a forest canopy in forest spray operations. The observed deposition patterns also indicate that the total cylinder deposition, and thus the local ventilation airspeed, may be reasonably estimated from the cylinder midline densities. For the beer can the midline-to-total ratio is about 0.15 for droplets in the 8 μ to 52 μ range. For the small cylinder, the appropriate factor is about 0.27.

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Session V
(Panel Discussion)
Weather Service Needs, Capabilities and Policies

Chairman: John Bethea

State Forester

Division of Forestry

Tallahassee, Florida

Weather Service Needs in Planning[1]

George W. Tourtillott[2/]

From my perspective as an administrator in the Forest Service the needs of the Weather Service are quite simple and straight forward - whatever it takes (methods, procedures, techniques, etc.) to provide land managers data and information to identify effects of proposed land management decisions on air and air quality, and to provide weather information as it may relate to land capabilities and management configurations.

In the context of the land planning process there is a manager at each level of our hierarchical organization, the Regional Forester at the Area Guide level, the Forest Supervisor at the Land Use Plan level, and the District Ranger at the project level. Each has decisions to make relative to the use of the land under his jurisdiction.

Meeting the needs of land managers received more emphasis recently with the passing of the National Forest Management Act of 1976. This Act will require an intensive and detailed land use planning effort on the National Forests over a relatively short period of time. To pull this off successfully, land managers are going to need precise data readily available to them, and proven analysis processes so that the answers they come up with are sound and defendable.

The Weather Service, or weather information, comes to bear in many facets of National Forest land use and project planning. I want to concentrate my discussion on land managers needs in two areas: Air quality and winter sports.

Air quality information for land use planning is needed at all planning levels from Area Guides to project planning.

As I said before, the same information is needed at each level, however, the closer to the ground the greater the need for more precise data.

In general, the information needed is:

1. Susceptibility of an area to air pollution from each pollutant - i.e. how much emission of a given pollutant can an area receive before the EPA air quality standard for that pollutant is exceeded. In other words, how big is the bucket?
2. What is the current air quality relative to each pollutant? Or how much of the bucket is already filled with pollutants and how much more matter can the area take before it exceeds the EPA air quality standard for that pollutant?
3. What are the expected emissions associated with each land use alternative or, will the alternative cause the bucket to runneth over, and if so, by how much?

The input data needed to arrive at this air quality information must generally come from existing data because we cannot wait one or two, or three years while it is put together - It's needed now.

The process for gathering data must be straight forward, easily understood and readily available to Forests and Districts so that it can be plugged into the plan. I cannot overemphasize this point enough. These boys at the Forest and District are going flat out and when they need some answers they need to be able to go to the machine and get it right back. The process cannot be something that it takes a Ph.D. to understand or a computer specialist to operate. In the "Technology Transfer" as it's called these days, it has to be taken out of the technical jargon and explained in language that the manager can understand and follow. It isn't a matter of having the smarts to figure it out - he just doesn't have the time to figure it out and so it won't be used. "For the want of a nail..." and so on.

And now the good news. The Mountain Meteorology Group at Rocky Mountain Forest and Range Experiment Station is developing and proving out a process to get at these very questions and processes. What I have seen of the information produced in Colorado on a Statewide basis, and for the Greater Yellowstone Cooperative Regional Transportation Study, it provides precise enough information for land use planning at the Area Guide and Forest land use planning level.

1/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, Nov. 16-18, 1976.

2/ USDA Forest Service, Denver, Colorado

But we cannot stop here. As the planning effort steps down to the project level, the level of detail increases and the location as to where developments or activities are to take place becomes more specific. The level of detail relative to air quality information must be stepped down accordingly.

At the Area Guide and Forest level, we are dealing with map scales of 1:500,000 or 1:250,000. At the District level, however, map scales are generally at 1 or 2 inches per mile. The process must be able to accept the same kind of input data at these more precise scales and provide output data and information adequate for use at these scales.

Land managers need a process that can be quickly and easily stepped down from one planning level to another.

Environmental Protection Agency standards are based on the "normal worst" atmospheric conditions that are likely to occur in the area. These conditions such as wind speed, temperature, barometric pressure, etc. can be defined. But land managers need to also know the probability of occurrence. Can he expect these conditions 10% of the time? Or 50%? Or once a year?

Closely associated with air quality - particually particulates - is visual management in the National Forests. It deals with the visual harmony among all parts of the landscape - landforms, vegetation, structures, water and air. The Forest Service objective of landscape management is to manage all National Forest System lands as to attain the highest possible visual quality commensurate with other appropriate public uses and benefits.

So the land manager needs Weather Service data and processes not only to work within EPA standards but to "attain the highest possible visual quality."

Emissions from certain activities or uses may be within established EPA standards but still result in degradation of the visual quality. At what point do suspended particulates become visible and adversely impact the view of the landscape? Under what conditions will emissions from a particular use or activity reach that point? How will particulates drift from their source and what will be their concentrations? Methods and procedures for the land manager to answer these and similar questions must be readily available to him.

Potential Winter Sports sites is another area where help is needed. Take for instance a potential site where the aspect appears right, the elevation appears right, the slopes and terrain appear right. But what of the wind speeds and patterns and what about the pattern of snow deposition? Can the Statewide data be brought down and identify these factors on a 10,000 acre area with a sufficient degree of reliability?

Can known weather data on one area be extrapolated to a nearby area and what are the key components that must be known in order to make the extrapolation?

How can we get an adequate weather picture on a potential Winter Sports site without having to install and maintain weather equipment in the area for a number of years or, what is the minimum data base needed on a new area in order to make a reliable extrapolation?

I have talked of two areas where land managers need help to adequately redeem their land use planning responsibilities. Some processes and procedures are already developed. With some I think the technology is there, but as indicated by the questions I have asked, the process needs further development and the job of figuring out how still needs to be accomplished.

Session VI
Biometeorology in Recreation and Land Use

Chairman: George Tourtillott

Director of Forest Service Lands and Recreation

United States Department of Agriculture

Denver, Colorado

quickly become bare under heavy ski traffic, especially if the weather warms up.

In addition to early-season grooming, most American ski areas carry out several types of intensive snow grooming throughout the winter. It is common practice, for example, to machine-pack new snow as it falls. This keeps the wind from blowing it off the old ski-packed surface and toughens it against displacement from ski traffic.

In spite of machine packing, sustained heavy ski traffic results in an uneven snow surface, especially on the steeper parts of the trails. This is accentuated by the wide acceptance of the short ski and the stiffer ski boot. This equipment makes it possible (and fashionable) for skiers with only modest skills to ski the steeper slopes. When this type skier gets in steep terrain, he tends to go farther out of the fall line and usually slides his turns more than an expert skier. As a result the skis push the loose snow into mounds, called moguls, which enlarge with time. Eventually the steeper portions of the trails are completely covered with moguls. For many skiers, such mogul fields are difficult and unenjoyable. To smooth such areas, large graders pulled by snow cats chop off the tops of the moguls and drag the loosened material into the troughs. Generally this operation is successful. At times, however, when the tops are cut off the moguls, the snow beneath is so coarse-grained and loose as the result of metamorphism that it spills down slope and leaves a bare spot. This condition requires additional grooming and packing, which is easier if there is new snow to mix with the older, granular snow.

Artificial snow-making is still another grooming practice recently installed in many areas. Special snow guns release a mixture of compressed air and water that forms snow crystals under proper weather conditions. At some areas entire trails are covered with artificial snow--at other areas only certain chronic trouble spots. As far as I know, there are no special meteorological problems associated with artificial snow-making so long as temperatures are below freezing and winds are not so strong they misplace the snow.

There is no doubt the smoothed, well-groomed ski trails contribute to the enjoyment of most skiers. Skiing these well-manicured and engineered trails does wonders for the ego and confidence of all but the most skilled skiers, who may wish more of a challenge. The earth-moving and grading necessary to produce such trails, however, often create serious problems that only become apparent during the spring thaw. Forest litter, low vegetation, and small natural drainages are often damaged by the grading so the melt water starts to erode the exposed soil. Water bars, artificial drains, and revegetation are necessary to stabilize the slope. Stabilization is often difficult and, at best, may take several years, especially at the higher elevations. In the meantime, there may be severe erosion on the slopes and in the overloaded stream channels.

FREQUENT SNOWFALL

Thus a second meteorological factor that is helpful for ski-area development is frequent snow falls all during the ski season. These snows are needed to repair the damage done by the ski traffic and to build additional base. Strange as it may first appear, very large snowfalls are often more of a hindrance than a help. A storm of 18 to 24 inches requires around-the-clock packing and grooming on the mountain, as well as extra effort to plow the parking lots and access roads. Such heavy storms also create problems on the major highways, often substantially increasing driving time from the population centers to the ski areas. They are also major factors in the release of snow avalanches which pose a threat to many ski areas and access roads.

WIND

Wind is another meteorological factor of considerable importance to ski-area development. Wind patterns in mountainous terrain are notoriously complex. An important contribution meteorologists could make to ski-area development is to devise ways to determine what wind-flow patterns will be on a mountain after considerable timber has been cut in strips down the mountain for ski trails, lift lines, and building sites. One engineering approach reported in the literature uses a scale model of the mountain and a sediment-laden water flume (Matthews 1975).

Wind erosion and deposition of snow plagues many ski areas, especially those that extend above timberline. Wind-scouring of the snow is particularly serious when steep pitches face the prevailing winds. Such places seldom get a heavy snow cover in the first place, and what they do get is loosened by the sliding action of the skis and carried away by the wind. On trails downwind of sparse or patchy timber, the snow cover is often uneven with scoured places alternating with deep drifts. Near the crest of ridges, snow is characteristically blown from the windward to the leeward side. This leaves the windy side too rocky to ski, and often creates cornices or dangerous

avalanche-prone snow-cushions on the lee side. Wind-scour also makes it necessary to shovel snow onto the unloading ramps of many lifts, or to cover the ramps with some artificial but skiable material --- such as rope netting or outdoor carpeting. The other extreme is exemplified by one large western ski area where the top terminal building for one of the lifts is buried in a snow drift and must be entered via a snow tunnel, while less than 100 yards away snow fencing is needed to provide enough snow to get the skiers started down the mountain. Good trail locations with careful attention to wind flow patterns can avoid many such problems; snow fences or other wind barriers have been helpful in numerous places. A few of the really tough problem areas, however, have resisted all efforts so far.

High winds also create safety problems for all types of aerial lifts. Winds blowing across lift lines cause the chairs, gondolas, or trams to swing and at times to become entangled in the towers. The only safe procedure is to stop operating the lifts when certain wind velocities are reached. Failure to do so has resulted in several lift accidents and numerous near misses.

As most skiers can testify, wind is also an important factor in skier comfort. Chairlift rides of 15 to 20 minutes are common on the bigger mountains. Only a few of these lifts have any type of protection for the riders. During cold weather, especially if snow is falling, a breeze of 15 to 20 miles per hour can lead to severe discomfort and at times to frostbite. The drag lifts such as T-bars and Pomas that keep the skiers on the ground and out of the wind, or the enclosed gondolas or trams, are much better for such conditions.

TEMPERATURE

Temperature is a third meteorological factor important in ski-area development. Warm temperatures soften the snow and quickly lead to poor skiing and eventually to bare spots. Alternating warm and cold temperatures, typical of sunny high elevations in the spring, result in snow conditions that vary greatly not only from place to place on the mountain at any given time but also from time to time at any given place. It is particularly annoying to be skiing down a trail and find your skis sticking and dragging in wet mushy snow in the sunny spots and shooting out from under you on the icy snow in every patch of shade. Warm mid-winter temperatures indicate the possibility of rain, and rain on snow is bad news at ski areas. During and immediately after the rain the snow is wet and heavy. It quickly turns to ice, however, as soon as the temperature drops. Both conditions are difficult and unpleasant to ski. Rain also loads the steeper slopes, weakens the snow, and sometimes leads to avalanching. Extremely cold temperatures (-25°C or -10°F) on the other hand, are not only uncomfortable and dangerous for the skier but also make the snow unusually hard and "sandy" under the skis. This type of snow is unpleasant and tiring to ski.

One of the many enigmas of the ski business is that, although cold temperatures are important for quality skiing, warm temperatures are preferred for the areas to be developed for hotels and houses. A steep north-facing mountain with a relatively broad valley that allows the sun to warm the lower south slopes makes a nice arrangement. When valley elevations are low, however, it is good insurance to design the lower ski lifts so skiers can ride the lift down the mountain. This allows skiing on the upper trails well after the lower trails are melted out.

ADDITIONAL METEOROLOGICAL FACTORS

Additional ski area problems that involve meteorology include proper architectural designs for snowy regions, temperature inversions, whiteout conditions, and snow avalanches.

There are a number of important factors when designing buildings for snowy regions (Bull 1973). Roof design is of primary importance. Typically heat leaks through the roof and melts some of the snow on the roof. The melt water runs down the roof until it encounters the cold eaves. Here it freezes. Additional melt water ponds up behind the ice dam and flows under the shingles into the building. The only solution is to have either a completely warm or completely cold roof. A warm roof must have heat piped all the way out to the eaves. Even then small ice dams usually form. A cold roof is really a double roof with a space for outside air to circulate between them. Both of these solutions are expensive. Yet the obvious shortcut of eliminating the eaves has proven disasterous. An ice dam still forms and causes early leaks plus icicles that tend to hit the building and break windows when they fall.

Any pitched roof should have the gables (ends) pointed toward the prevailing winds to reduce snow drifts that result in uneven loads and serious design problems. Doors, walkways, or other places where people congregate should be at the ends of the building and not under sloping roofs. The current trend is toward flat roofs with a gentle slope toward a center

drain down through the warm building. The wind keeps most of the snow blown off the roof, and the simple shape makes design problems easier. I know of one building with a complex, ornate roof that has so many ice dams and icicles the management eventually installed electric heating elements in the numerous gutters and roof valleys. At another area, the snow on the roof of the upper gondola terminal forms two large cornices. One cornice overhangs the area where people stop to put on their skis; the other overhangs the door to the first aid room. This building has since been modified to reduce these hazards.

The intense temperature inversions typical of snow-covered mountain valleys become very noticable and troublesome when the number of homes and auto traffic increases. Smog around the base area at some of the ski resorts has recently become so bad that serious thought is being given to prohibiting the use of all fireplaces during temperature inversions. This would be quite a blow to the classic image of mountain homes and après ski life in which fireplaces figure prominently.

Flat light or whiteout conditions occasionally become severe enough to curtail skiing and greatly restrict highway driving. Whiteouts occur during blowing snow events in snow-covered, treeless areas. The uniform, diffuse light with no shadows, no dark objects, and no horizon gives the impression of floating in a big bowl of milk. When this condition develops on the ski slope, one quickly looses all perspective of slope steepness and motion. It is very disconserting in steep terrain to be certain you are standing motionless or moving very slowly on your skis, only to have your arm whip back suddenly when your ski pole touches the snow.

I'll only mention here that snow avalanches are a safety problem along some mountain roads and in some ski areas. Avalanches result when the snow load on steep slopes exceeds the strength of the snow. The amount of snow and its strength at any given time, and the changes that take place with time, are correlated with weather conditions. Perhaps the interesting topic of snow avalanches can be discussed at some other time.

MOUNTAIN WEATHER FORECASTS

Short-term mountain weather forecasts have been notoriously poor for most western mountain areas. To some extent this reflects the higher priority set on forecasting for the more heavily populated, nonmountainous areas. To some extent it may also reflect the lack of good mountain reporting stations or the added difficulty of forecasting for the more complex terrain. Whatever the reasons, the fact is that, at this time, the day-to-day operations on most ski areas are carried out with an almost complete disregard for weather forecasts, and the skiing public has little information on which to make its decisions. The greater number of people in the mountains and the fine communication systems that now exist on many of the larger ski areas mean more possibilities for good mountain reporting stations than ever before. To be most useful, mountain weather forecasts should cover conditions on the ridges and mountain tops, not just valley locations. Snowfall amounts, durations, and intensities, temperatures, wind speeds, and stability conditions are the primary features that will allow the ski areas to schedule their work crews and the skiers to make their travel plans.

A FEW NON-METEOROLOGICAL FACTORS

Although we have been discussing meteorological problems, the successful location and development of a new ski area involves many problems that are unrelated to meteorology. For example, the availability of private lands for the base area and for real estate development is extremely important. Other important considerations are: easy access by public and private transportation from large population centers; proximity to other successful ski areas; sufficient long-term financing at reasonable rates; and evaluation of the impact to be expected on the environment and local economy. These and other economic, political, and social problems as well as the meteorological problems we discussed must be dealt with early in the planning process.

SUMMARY

In summary, I feel there are two major meteorological problems that are important for ski area development and smooth operation.

1. The prediction of the localized wind patterns to be expected on a given mountain if a certain set of trails and lift lines are built.

Certain trail and lift locations are dictated by the terrain and general area layout but many are not. In either case it would be highly desirable to be able to consider the wind factor when choosing among several possible trail patterns and in determining the final details of trail width and alinement pitch by pitch down the mountain.

2. Detailed and quantative 24-hour forecasts of precipitations, wind and atmospheric stability conditions for specific ski areas.

Precipitation forecasts would help greatly in scheduling manpower and equipment for grooming, snow plowing, avalanche control, and artificial snow making. Wind forecasts are important for lift safety and for the operation of certain lifts that run only during good weather. Stability forecasts are becoming important for anticipating temperature inversions severe enough to require restrictive measures to reduce smog and air pollution in the valleys.

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The Application of Forest Edge Meteorology to Environmental Impact Assessment and Development Planning[1]

David R. Miller[2]

Abstract.--The components of the two dimensional energy budget at a hardwood forest edge are presented and analyzed. Field experiment results indicating the magnitude of the various energy budget components at forest-development interfaces are presented. The usefulness and application of this type of knowledge to aid with the minimization of the local environmental impact of developments in forested areas is discussed.

INTRODUCTION

Urban encroachment into forested areas is one of the major land use changes occurring in the eastern U.S. Over the years urban and suburban designers have suggested leaving "green belts" or other arrangements of natural vegetation as a rather vaguely defined environmental buffering system.

Recently there have been numerous attempts to institute programs which would routinely assess the environmental impact of "proposed" local developments before the developments are begun. These efforts have been quite valuable in pointing out which disciplines lacked information that can be applied on a practical local basis.

For example, the Connecticut Environmental Review Team described by Miller and Thomas (1974) has made on site impact assessments of some 80 proposed developments in rural eastern Connecticut. Approximately 80% have been in forested areas. In all of these cases the limitations of the soil and microhydrological systems involved could be detailed from standard survey data with a minimum of on site data gathering. This was not true with regard to the meteorological effects of the developments. Local microclimate changes and their importance in the mesocale air pollution or heat island could only be stated very generally. Little can be detailed on the effects of suburban vegetation, spaces and structures on the "microscale" meteorological processes.

The numerous mesoscale investigations of the urban atmospheres are difficult to transfer into specific design criteria for individual developments because they are an integration of the effects of the microclimatic patchwork. Local heat balance considerations are considerably more complicated than can be inferred from general average heat island data. The suburban or urban surface is dentated by streets, buildings with verticle walls and partial canopies variously exposed to solar radiation and each other. Figure 1 demonstrates some differences in surface temperatures that are common in this environment. It shows a parking lot surface reaching 50° C while a forest canopy wall facing the parking lot remains at about 20° C.

It's this edge environment which so far has precluded the transformation of micrometeorological knowledge to engineering design criteria.

1/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology. St. Louis, Mo. Nov. 16-18, 1976.

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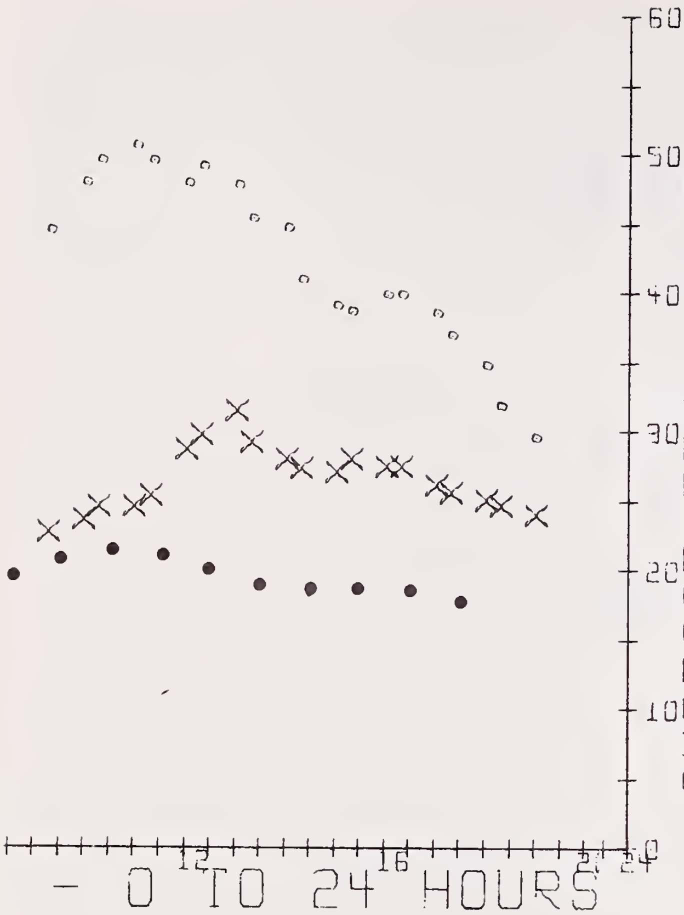


Figure 1.--Surface temperatures of an asphalt parking lot (o), a south facing, verticle oak forest wall (•) and soil beneath the forest (x).

We are approaching a technology transfer capability with regard to the local radiation regimes in this edge environment. A recent project by co-operators in the Pinchot Consortium for Environmental Forestry Research (Stark and Miller, 1975; Plumley, 1975; and Herrington and Vittum, 1975) has pointed out the roles of various arrangements of vegetation ameliorating the urban and suburban radient energy environment. Figure 2 (from Stark and Miller, 1975) shows the relationship between radient energy loads and the percentage of the hemispherical view in non-natural conditions (vegetation, sky). It demonstrates the type of relationship definition that is necessary for local decision makers to judge the tradeoffs being made.

But the local radiation environment is only one part of the problem. The major source of confusion when defining the physical vegetation - development interactions is horizontal energy transport or <u>advection</u>.

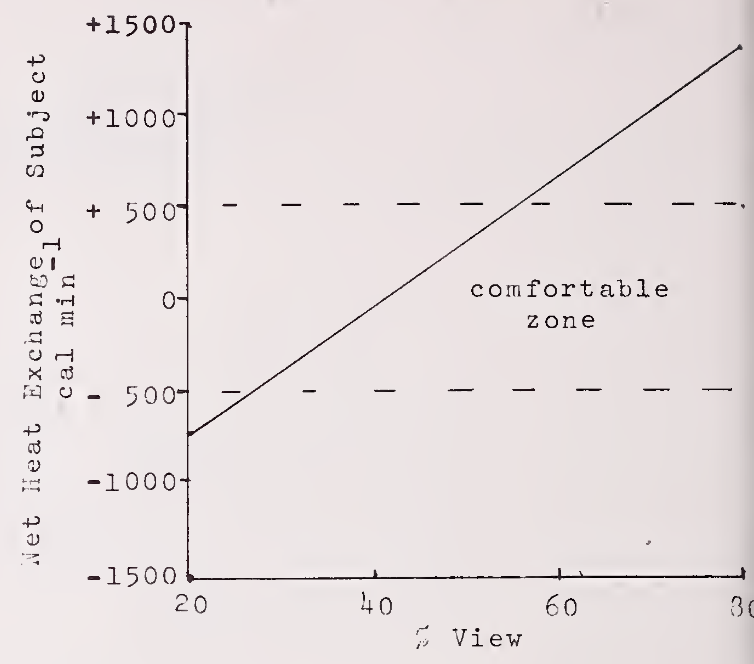


Figure 2.--Average summer midday net heat flux for a human subject as a function of the proportion of his hemispherical view covered with synthetic materials (i.e. cement, brick, etc.), Storrs, Connecticut.

Tanner (1958) described two different ways in which advected energy is supplied to plants. First, the energy is supplied to the canopy vertically from an overlying mass of advected air. He called this the "oasis" effect. The second is the case where advected energy, generally sensible heat, is moved horizontally through the canopy. This he called the "clothesline" effect.

The three dimensional form of the forest-urban interfaces, together with the large amounts of sensible heat produced in the urban settings, suggests the possibility that horizontal advection into and from adjacent stands may be significant. If these exchanges can be defined then the secondary effects of this energy exchange can be predicted.

THE TWO DIMENSIONAL ENERGY BUDGET

The energy exchanges of a volume of forest of height (h) located at a stand edge are diagramed in Figure 3. The forest exchanges radiation (R_n), latent heat (E), and sensible heat (A) both vertically (subscript z) and horizontally (subscript x) with the sur-

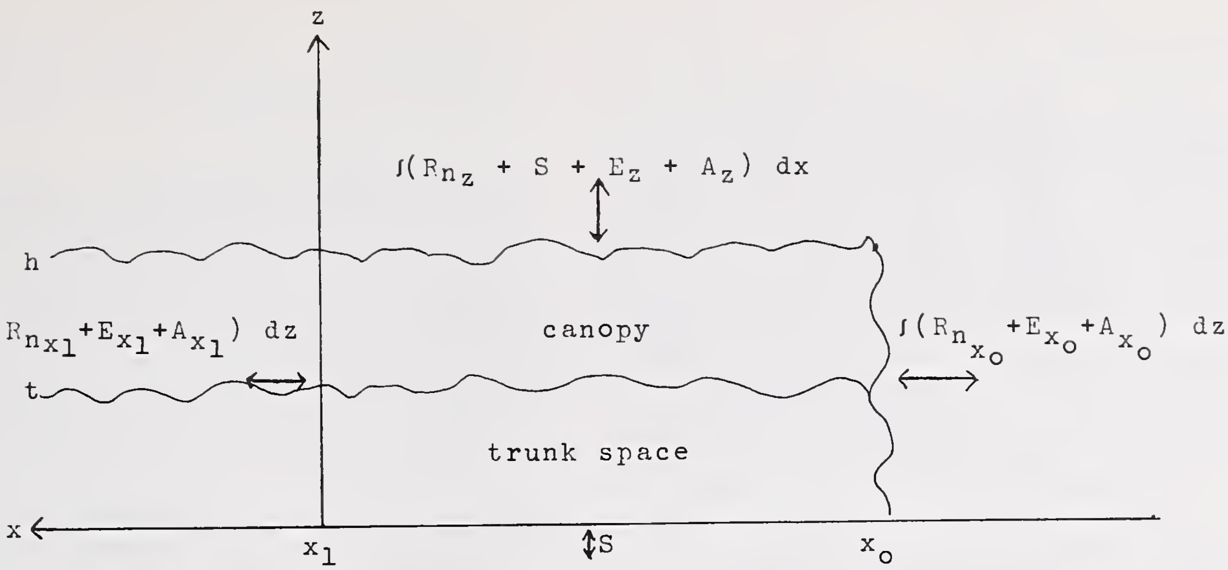


Figure 3.--Diagram of the two dimensional energy budget at a forest edge.

rounding atmosphere. There are also horizontal and vertical exchanges of these entities between various parts of the canopy. At the lower boundary heat is exchanged with the soil (S).

The steady state balance of the energy gains and losses of the edge cross section of height (h) and extending from the edge (x_o) some distance (x_1) into the forest can be written:

$$0 = \int_{x_o}^{x_1} (R_{n_z} + E_z + A_z + S)\, dx + \int_{z=o}^{z=h} (R_{n_{x_o}} + E_{x_o} + A_{x_o})\, dz - \int_{z=o}^{z=h} (R_{n_{x_1}} + E_{x_1} + A_{x_1})\, dz \qquad (1)$$

If the horizontal distance $X_1 - X_o$ is large enough to avoid edge effect and the horizontal divergence of R_n, A and E can be assumed negligible beneath the canopy of a homogenous forest, then the third term of equation (1) can be neglected reducing it to:

$$0 = \int_{x_o}^{x_1} (R_{n_z} + E_z + A_z + S)\, dx + \int_{z=o}^{z=h} (R_{n_{x_o}} + E_{x_o} + A_{x_o})\, dz \qquad (2)$$

Verticle Exchange

The verticle components of the energy balance above the edge forest canopy are the same processes as those normally described above agriculture and forest canopies. But the proximity to the edge affects the quantities involved in the verticle exchanges due to the variations in the internal boundary layer thickness. (See Plate, 1967; Montieth, 1973; and Rosenberg, 1974 for discussions of the boundary layer). The rate at which the boundary layer grows with distance from the abrupt change in roughness caused by a stand edge varies somewhat with the type of surfaces involved. In the case of hardwood forests, Shinn (1971) calculated, from Sadah's (1974) measurements of shear stress in a wind tunnel with a simulated forest edge, that the disturbed boundary layer thickness (γ) and the internal boundary layer thickness (γ') (as defined by Plate, 1967) grew identically and linearly with distance from the leading edge up to 25 h (h = tree height):

$$\Delta\gamma = .08x \qquad (3)$$

Since the boundary layer depth is a function of distance from the stand's leading edge the conditions will change with wind direction. If the wind is blowing from the stand the edge volume will probably be well within the internal boundary layer equilibrated to the canopy.

R_{n_z} and S are not effected by proximity to the forest edge. But E_z

and A_z are functions of the boundary layer depth.

Evapotranspiration measurements in low growing plants downwind from a dry edge have been made several times (Rider et al, 1963; Hand, 1964; Millar, 1964; Dyer and Crawford, 1965; Lang et al, 1974) and always showed decreasing vapor-flux with distance from the edge. The form of the relationship is an asymptotic one first suggested by Philip (1959). He suggested that E_z would vary downwind from a dry boundary according to:

$$E_z = ax^{-P} + b \qquad (4)$$

In equation (4) a, p, and b are constants. "a" is the amplitude of additional evapotranspiration at the edge caused by the availability of advected (horizontally transported) sensible heat (A) at the edge. "p" describes the rate of decay of this amplitude downwind and is probably uniquely related to the internal boundary layer thickness (γ').

"b" is not really a constant but is the E flux rate in the interior of the stand where the internal boundary layer has fully developed. In this case the interior evapotranspiration rate (b) can be described by the commonly used, one-dimensional flux-profile relationships within the boundary layer.

$$\beta = \frac{A_z}{E_z} = \frac{\rho Cp}{L} \left(\frac{K_a}{K_e}\right) \frac{\partial T/\partial z}{\partial e/\partial z} \approx \frac{\rho Cp}{L} \left(\frac{\Delta T}{\Delta e}\right) \qquad (5)$$

and

$$b = \frac{R_n - S}{1 + \beta} \qquad (6)$$

Where: T is air temperature
e is vapor pressure of water in air
Ka is an exchange coefficient for sensible heat
Ke is an exchange coefficient for water vapor
ρ is air density
Cp is the specific heat of air at constant pressure
L is the heat of vaporization of water

Combining equation (4) and (6) gives:

$$E_z = ax^{-p} + \frac{R_{n_z} - S}{1 + \beta} \qquad (7)$$

Where $\frac{\Delta T}{\Delta e}$ is measured with adequate downwind fetch from the edge.

Sensible heat flux (A_z) downwind from the edge will be produced at the top of the canopy by two different processes. One is the sensible heat produced by contact of the air with the radiationally warmed canopy. The second is sensible heat forced (advected) through the stand edge which is transported upward through the canopy.

The amount of sensible heat available to flux upward will dissipate with distance into the stand. Therefore the sensible heat transport with depth into the stand (x) will decay in a similar manner to E, i.e.:

$$A_z = c\,x^{-d} + e \qquad (8)$$

Where c and d are constants and e is the verticle sensible heat flux above the canopy in the interior of the stand where it can be described by the verticle gradients and partitioning the verticle energy balance:

$$e = \frac{R_{n_z} - S}{1 + 1/\beta} \qquad (9)$$

$$A_z = cx^{-d} + \frac{R_{n_z} - S}{1 + 1/\beta} \qquad (10)$$

Horizontal Exchange

Sensible heat flux through the edge depends on the wind speed (u) and horizontal temperature gradients.

$$A_{x_o} = \int_{z=o}^{z=h} \bar{u}\,\frac{dT}{dx}\,dh \qquad (11)$$

Fritchen et al. (1970) and Raynor et al. (1974) have indicated from dispersion studies that the wind approaching a forest edge from a cleared area tends to split into two flow pathways - above the forest and into the trunk zone. With a smaller flow of air entering the side of the crown. Thus indicating that flow into the edge should be considered in two layers consisting of the trunk layer, of height t, and the crown layer of height, h - t:

$$A_{x_o} = \int_{z=o}^{z=t} \bar{u}\ (dT/dx)\ dz$$

$$+ \int_{z=t}^{z=h} \bar{u}\ (dT/dx)\ dz;$$

$$\frac{dT}{dx} \geq o \qquad (12)$$

A similar expression for latent heat transport can be written:

$$E_{x_o} = \int_{z=o}^{z=t} \bar{u}\ \left(\frac{de}{dx}\right)\ dz$$

$$+ \int_{z=t}^{z=h} \bar{u}\ \left(\frac{de}{dx}\right)\ dz;\ \frac{de}{dx} \geq o \qquad (13)$$

Equations 11-13 assume that $\bar{u}$ is the major component of transport through the edge when the wind is near normal to the edge.

A FIELD STUDY

A field study of these energy budget parameters was conducted during 1973-75 in Storrs, Connecticut. A south facing Black Oak forest wall adjacent to a large asphalt parking lot was used. Radient energy fluxes and horizontal and verticle gradients of wind speed, air temperature and vapor pressure were measured. The site, experiments conducted, and data collected have been listed in two reports, Miller et al. (1975) and Miller (1976).

Figure 4 demonstrates the general magnitude and locations of the horizontal and verticle gradients at the edge. It shows midday two dimensional gradients of vapor pressure and temperature at the edge. The locations of these gradients change as a function of windspeed and direction.

During periods with the wind blowing from the stand the first terms of equations 7 and 10 can be ignored because in these cases the distance from the leading edge (x) is very large. Therefore utilization of the measured gradients and energy balance parameters in the second terms of equations 7 and 10 allow the estimation of sensible and latent heat flux. Figure 5 shows the energy balance from such a day, July 11, 1974.

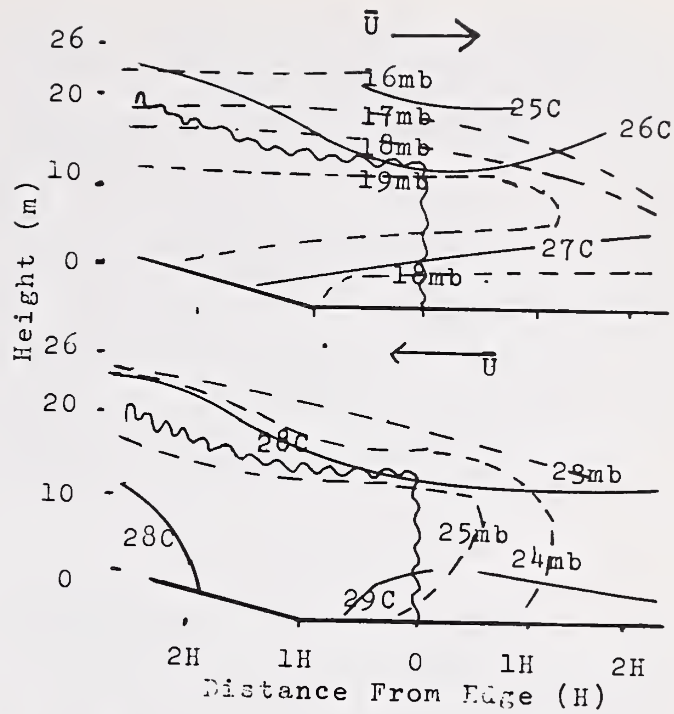


Figure 4.--Midday air temperature isotherms (solid lines) and air vapor pressure isobars (dotted lines) across the parking lot-forest edge with the wind blowing out of the forest, Aug. 22 (top) and into the forest, Aug. 24, 1974 (bottom).

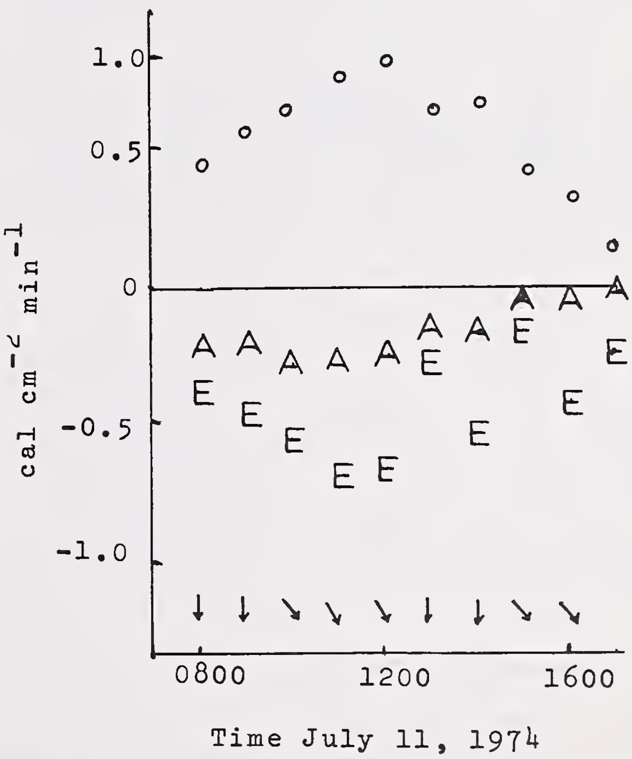
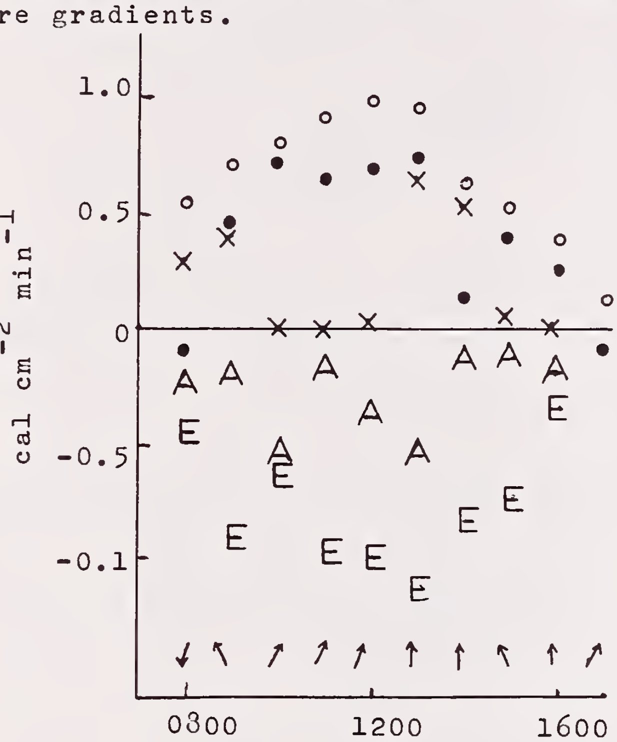


Figure 5.--Verticle energy budget witn the wind blowing from the stand to the parking lot, July 11, 1974 (O is R_{n_z}; E is E_z; A is A_z; and the arrows indicate wind direction).

Figure 6 shows the energy balance terms on a day (June 14, 1974) with the wind blowing into the stand. In this case energy is being added to the side of the stand. The amount of sensible heat advected into the side of the stand (A_x) was estimated by equation 12 utilizing the measured wind speed profiles at the edge and the horizontal temperature gradients.



Time June 14, 1974

Figure 6.--Energy budget with the wind from the parking lot to the stand, June 14, 1974. (o is R_{n_z}; • is R_{n_x}; x is A_x; A is A_z; E is E_z; the arrows are wind direction).

R_{n_x} was calculated from: the potential solar beam on a 90° south slope (R_{90}), after Fernival and Riefsnyder (1969); and atmospheric transmission factor (R_s/R_o), where R_s is the measured short wave radiation on the horizontal and R_o is the solar beam on the horizontal; and the on site determined regression of net radiation (R_{n_z}) on R_s for the day.

$$R_{n_z} = -.14 + .82\ R_s \qquad (14)$$

Thus,

$$R_{n_x} = -.14 + .82\ [R_{90}(R_s/R_o)] \quad (\text{cal cm}^{-2}\ \text{min}^{-1}) \qquad (15)$$

The energy budget shown in Figure 6 then is:

$$R_{n_x} + A_x + R_{n_z} - S = LE_z + A_z \qquad (16)$$

Comparison of the two days gives an indication of the effects of the added energy on water use by the trees. On the day with the wind from the forest seventy-six percent of (R_n-S) was utilized to evaporate water (β=.32). On the day with the wind into the forest the evapotranspiration rate was approximately doubled. Sixty-nine percent of the total energy available ($R_{n_x} + A_x + R_{n_z} - S$) was used to evaporate water ($\bar{\beta}$ = .45).

The increase of β with the wind into the stand indicates that although the transpiration rate was increased a large proportion of the added energy was transported out through the top of the stand as sensible heat. Apparently energy was supplied faster than the trees were able to supply water.

PROBLEMS REMAINING

The edge energy balance research described above has given us some insight into some of the local environmental effects of development in woodland areas. But before the models can be utilized to predict effects of proposed developments at a given site the physical relationships involved in the first terms of equations (7) and (10) will have to be defined. The rates of decay, p and d, must be specified before the relative efficiency of any given geometric pattern can be determined. They are complicated functions of the edge momentum balance which is not understood.

Probably, the most immediate problem which is delaying practical applications is the lack of a method to independently measure short term transpiration rates in large trees. Not only do we need it to define parameters such as p but independent measurements of E are necessary to test the usefulness of present energy balance and aerodynamic techniques in the edge environment. Only Fritchen (1973) has made measurements of short term transpiration from a single large tree "in situ".

A continuing major problem is trying to predict microclimatic phenomena

on a site from general climate information with insufficient historical data both temporally and spacially.

SOME APPLICATIONS

If, through further research, we find that significant amounts of sensible heat can be advected through edge stands, and that the evapotranspiration response of the stands can be predicted, then applications can be made to several current land use problems. An obvious one is designing the most efficient arrangements of tree stands to reduce the urban heat island.

Another is in conjunction with land disposal of sewage effluent. The "living filter" system (Sopper and Kardos, 1973) does not work very well in areas like Connecticut which average only 20 inches of soil, 25 inches of annual evaporation and 40 inches of rain. Thus arrangements of land uses which might increase E in areas where land disposal of liquid wastes is proposed would be very helpful.

Also, the fact that the vegetation limited the rate of water use in the above study brings to mind another possibility. Stand management criteria might be established to increase or decrease evapotranspiration of edge stands. If the sensible heat moving through the edge would move further horizontally before rising through the canopy, more of it might be utilized to evaporate water. This might be accomplished by removing understory obstructions and edge vegetation while maintaining a solid overstory.

Bergan (1975a, 1975b), Shinn (1971), Buffo (1972), Sadah (1975) and others have recently added considerably to our knowledge of air flow in forest openings and at edges. Their work together with the extensive body of knowledge of air flow around blocks and rows of trees (i.e. Van Eimern, 1964; Miller et al., 1975; Plate, 1970 and others) should allow the development of some specific guidelines for utilizing trees in urban areas for wind control.

Modification of the local vegetation geometry has a number of secondary effects. Consequences of vegetation mangement can be pointed out in such areas as energy conservation, human comfort, phenological cycles, and snow control. But, an adequate knowledge of the basic energy and momentum relationships at local forest-urban edges is necessary before these effects can be detailed.

ACKNOWLEDGEMENTS

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Propagation of Noise in the Out-of-Doors[1]

L. P. Herrington[2]/

Abstract.--The current state of knowledge concerning the propagation of noise in the out-of-doors and the effects of vegetation on the propagation process are reviewed. Based on this knowledge suggestions are made for the partial solution of acoustic problems present in recreation areas. Proper acoustic planning can reduce noise complaints.

INTRODUCTION

Noise, or unwanted sound, is an ever-present part of the environment when people are present. In general, the more people, the more noise. Since by definition noise is unwanted, it is usually considered objectionable and designers and planners of recreational facilities should consider the acoustic environment early in the planning process.

The attempt is often made to use land forms and vegetation to control noise. However, at the present time the propagation of noise over and through forested land is only partially understood. In this paper I will review some of the basic findings of the last several years and will discuss the application of these findings to recreational land use planning. A great deal of this work has been carried out by scientists working with the U.S. Forest Service, Pinchot Institute, through the Consortium for Environmental Forestry Studies.

PHYSICS OF NOISE

Description

Noise, or acoustic energy, is described basically by quantity and quality. Ambient noise is the more or less steady noise normally present in a given area for which it is hard to determine the exact source. Intrusive noises are louder noises, such as horns, trucks in a stream of auto traffic, jack hammers, children yelling, etc. Quantity is the energy in the noise signal while quality is the distribution of that energy over the acoustic frequency range of 20 to 20,000 Hz (Hz is for Hertz or cycles per second). Figure 1 compares both the quality (spectrum) and quantity of noise for a city street and a rural park. Quantity can be measured as Sound Pressure Level (SPL) and this measure is expressed in decibels. The SPL scale is related to the logarithm of acoustic energy and to the sensation of "loudness". An increase in SPL of 10db is sensed as a doubling of loudness. Measurements of SPL are usually made with instruments which can be made to respond to the various frequency components of a noise signal in a way similar to that of the human ear. Such measures are designated by dbA.

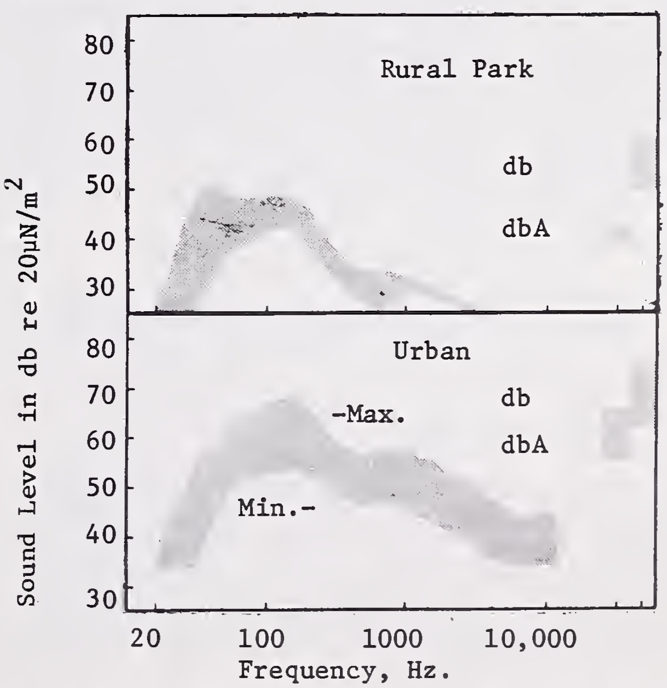

Figure 1. Third octave spectra, dbA, and db (flat, 20 to 20,000hz) for a typical urban area and a rural park. (Herrington 1974)

1/Paper presented at Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov. 16-18, 1976.

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Variation in sound level over time is another important characteristic of noise. The more variable the noise environment the more objectionable people find that environment. Generally increasing variability means increasing amounts of intrusive noise. The most common statistical description of this variability is the measurement of the sound levels which are exceeded 10, 50, and 90 percent of the time. In fact, the level which is exceeded 10 percent of the time alone has been found to be a good predictor of community reaction in some cases.

Other more complex estimators of community reaction, such as the Community Noise Equivalent level (CNEL), are adjusted for season (windows open or closed), ambiant noise levels, and community attitude toward noise in addition to variability (EPA 1972).

Propagation

Acoustic energy is propagated through the atmosphere from a source to a receiver as a moving wave of atmospheric pressure variation. These waves spread spherically from the source with a resultant loss in energy per unit area. On the SPL Scale this results in a reduction of 6db for each doubling of distance. A truck which produces a SPL of 100db at 50 feet will produce levels of 94db at 100 feet, 88db at 200 feet, etc. In addition to the reduction of SPL with distance due to spherical spreading there will be reductions by scattering, reflection, refraction, diffraction and absorption of the acoustic energy. This additional attenuation is called excess attenuation. Excess attenuation in db loss per unit distance is the usual way in which the losses due to vegetation and land form are expressed. Another way to express these additional losses is by means of an insertion loss (McDaniels and Reethof 1975). The insertion loss is simply the difference in SPL measured with and without the presence of the structure being examined.

Atmospheric Effects

Both the wind and temperature structure of the atmosphere have important effects on the propagation of acoustic energy through the atmosphere. The velocity of sound varies directly with temperature. When the land surface is hot and the temperature of the atmosphere decreases with height (normal daytime condition), the acoustic wave will be refracted away from the surface since the wave front will travel faster near the surface. Under these conditions sound levels will decrease faster than expected with distance.

At night when the land surface is cold and temperature increases with height (inversion condition) the acoustic waves will be refracted toward the surface with the result that noise levels will be higher than during the day; i.e. excess attenuation will be less. Wind has a similar effect since wind speed generally increases with height. Thus there is less attenuation for downwind propagation and greater attenuation for upwind propagation. Of the two the temperature effect is the more pronounced. The two effects can, of course, mutually cancel or add.

Effects of Vegetation on Noise

There has been considerable progress in recent years in developing an understanding of the propagation of acoustic energy out-of-doors (Herrington 1974) and of the role that vegetation plays in the propagation process. Acoustic energy can be propagated over or through vegetation with different losses. Vegetation can also add to the noise environment. Some pertinent results are summarized below.

1. For acoustic energy propagating beneath the forest canopy an excess attenuation of approximately 6db/100 feet (range 2db to 9db per 100 feet) has been found (Table 1). (Bjorenson 1971, Herrington and Brock 1976, Frank 1971, Leonard and Herrington 1973, McLoughlin 1975, McDaniels and Reethof 1975).

2. There tends to be more attenuation at the mid-frequencies (250-8KHz) than at higher or lower frequencies (Bjorenson 1971, McLoughlin 1975, Aylor 1972) but there is much inconsistency in the data (See Table 1). The most common pattern is for the high (2000-4000Hz) and low (125-250Hz) ends of the spectrum to be little attenuated while the mid-frequencies (250-2000Hz) are attenuated by approximately 10db/100 feet.

3. There is evidence that noise progagating over the forest is attenuated relatively little. Brock (1975) found an average excess attenuation of -0.1db/100 feet. Bjorenson (1971) noted that for sources outside the forest openings in the forest canopy resulted in a significant increase in sound level beneath the opening when the opening was at least as wide as the forest was high under inversion atmospheric conditions.

4. It has been shown that the forest floor is the absorbing medium in the forest. The more porous the surface the higher the absorption. Vegetation acts primarily as scattering elements (Aylor 1972, McDaniels and Reethof 1975). Scattering appears to be related to perceived aerial biomass (McLaughlin 1975).

5. Wind-break structures have been shown to produce insertion losses of about 10db and

Table 1.--Excess attenuation of selected cover types in order of increasing perceived aerial biomass.[1/]

Type	dbh in.	Height ft.	Ave. Excess Attenuation per 100 ft. db re $20 \mu N/m^2$	Freq. of max. attenuation Hz	Notes
Bare Earth	-	-	1.2	500	unused road
Grass	-	-	1.2	250,1000	6-10 in. high
Hardwoods[2/] w/o foliage	1-26	50-70	3.8	250,2000-4000	brush understory
Red Pine[3/]	5-6	50-55	4.4	250-1000	plantation, 6 x 6 ft.
Hardwoods[2/] w/ foliage	1-26	50-70	5.2	250-4000	brush understory
Norway Spruce[4/] short	3-4	15-30	3.8	250-1000	plantation
Cedar[5/]	4-5	25-30	6.1	500-1000	visually dense
Norway Spruce[4/] open	5-6	45-55	5.6	250	natural pruning
Norway Spruce[4/] dense	5-6	40-45	8.4	250-4000	no pruning

1/ After McLaughlin 1975
2/ Northern hardwood type
3/ Pinus resinosa
4/ Picea abies
5/ Thuja occidentalis

barriers of berms and vegetation have also been shown to be effective (Cook and VanHaverbeke 1971, 1974). These conclusions were based on daytime data only, however.

6. Vegetation can produce "masking" sounds when wind rustles the leaves (Brock 1975, Daily and Redman 1975). During the day in a moderate wind SPLs of 30 to 40dbA can be produced while at night, under calm conditions, the ambient noise levels will be 20 to 30dbA. This change in ambient level can change the "intrusiveness" of other noises. Running water is also a source of "masking" noise.

HUMAN RESPONSE TO NOISE

Basically people will be sensitive to the magnitude, quality, and temporal distribution of acoustic energy in a noisy situation. Generally, as the noise becomes louder, more people will complain and the complaints will become more vigorous. There is considerable variation in individuals' responses, particularly at low sound levels but when sound levels reach 70 to 80dbA dissatisfaction will be high and there will be more consensus of opinion (EPA 1972). Sound levels which will trigger complaints will also depend on the expectations of the people.

Noises which are not tolerated in campgrounds may well be acceptable in the city - by the very same people! Application of the corrections made to the Community Noise Equivalent Level for ambient noise level and community attitude indicates that for people in rural areas sound levels of approximately 70 dbA will result in vigorous complaints (65dbA if the noise includes intermitent sounds) while there will be no reaction where levels are below 45dbA. Dailey and Redman (1975) have specified "standards of insulation" for prinsine, primitive, and portal situations in roadless area campsites. The standards are for the level of noises which will not be audible between camps and are, respectively, 48, 60, and 70dbA. The more pristine the area the less noise is tolerated and the more attention must be paid to acoustic planning.

A very important aspect of the human reaction to the noise environment is the fact that people will be most sensitive to noise at night when ambient levels are low and intrusive sounds stand out. In addition, people expect quiet at night. A general rule of thumb is that acceptable noise levels will be 10dbA lower at night than they were during the day (half as loud).

APPLICATION TO RECREATIONAL PLANNING

There are a myrid of noise problems which can and do occur in recreational areas. These range from the traffic noise problems of barren campgrounds next to interstate highways to people noises in wilderness areas. Generally, however, the problems will fall into one of two categories: problems resulting from noise sources outside the area and problems resulting from noise generated within the area.

In attacking these problems the four parts of the problem suggested by Dailey and Redman (1975) in their paper on campsite spacing form a good starting point. These are:

1. Identification of the intrusive noises which must be screened. Depends on type of facility and expectations of users.

2. Measurement or estimation of ambient noise levels.

3. Determination of the presence of, or possibility of construction of, attenuating structures.

4. Identification of site features which can block the visibility of noise sources.

To these I would add that there must be separate evaluations for day and night since both people and conditions will change with the time of day.

When 1 and 2 have been accomplished and the amount of attenuation needed has been estimated, attention can be directed to 3, which is the subject of this paper. How can existing knowledge of noise propagation and the role of vegetation in noise control be applied here?

In the case of noises originating outside the facility the best rule, assuming that the source can not be quieted, is one of distance. The further away the sources the lower the received sound level. Beware, however, of inversion conditions coupled with wind from source to receiver since under such conditions intrusive noises from distant sources can be heard and identified. This could be a problem in wilderness areas where people do not want to be reminded that other people, let alone highways or railroads, are around.

For campgrounds a second step is to see that the campsites are located beneath a closed forest canopy with few holes. This suggestion is based on the fact that acoustic energy passing over the forest is attenuated much less than that passing through the forest. Sound levels will increase at night in the vicinity of large holes in the canopy.

The placement of areas requiring quiet so that barriers such as hills or ridges are between source and receiver will also help. The barrier should not be located midway between source and receiver but as close as possible to either one for maximum effectiveness. Under inversion conditions noise may still pass over the barrier and be refracted down toward the chosen site.

The masking sounds produced by moving water may be used to screen intruding noises. The closer the site to the water the more effective the masking since the sound of the water also decreases 6db for each doubling of distance.

In order to maximize attenuation of sound generated within the areas the amount of scattering and absorbing material must be maximized. This can be done by providing forest cover with considerable amounts of understory vegetation. The large amount of vegetation will result in a great deal of scattering of the sound and the understory vegetation will prevent compaction of the soil thus maintaining soil absorptivity. The understory vegetation will also provide visual screening and, in breezy conditions, provide additional masking. Given a site structure and an estimate of the excess attenuation provided by that structure the distance between campsites can be determined so that noises below a specified level generated at one campsite are not heard at the next under most conditions (See Dailey and Redman 1975).

In all of the above discussion I have treated only the acoustic aspects of the problems of recreational area planning. The solutions suggested here must, of course, be traded-off against other considerations.

SUMMARY

A little knowledge of outdoor acoustics can go a long way toward providing more acceptable recreation areas and should prevent many needless acoustic blunders. Facilities can be located to minimize the acoustic dissatisfaction of users. Although vegetation is no panacea for noise problems knowledge of the basic effects of vegetation on noise can allow successful application of vegetational control to some noise problems.

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Air Pollution Potential in the Piceance Basin[1]

E. A. Howard, III[2/]

Abstract.--The assessment of air quality degradation caused by the anticipated development of oil shale in the Piceance Creek Basin of western Colorado was done by comparing the results from commonly used mathematical models and applicable air quality standards. Available emission rates combined with episode meteorological conditions produced ambient concentrations which would restrict full-scale operations if air quality standards are not to be violated.

INTRODUCTION

Our current standard of living is based upon the availability of inexpensive and abundant energy which we have enjoyed in the past. Fluctuations in availability have brought about cognizance of the fact that oil and gas reserves are limited in extent and that sources of supply are becoming less and less reliable. Questionable sources and fluctuating prices on the international market serve to enhance the desirability of becoming energy self sufficient to as high a degree as possible. Fortunately, the United States does have extensive oil reserves and needs not be wholly dependent upon foreign sources. If current domestic demands for oil are to be met in the context of energy independence, however, and if prices and supplies are controlled by foreign forces, then new domestic sources must be developed.

A domestic energy source not yet developed is the oil derived from kerogens locked within the extensive shale formations of Wyoming, Utah, and Colorado. The amount of oil believed recoverable from these shale deposits has been estimated at nearly one trillion barrels. Since the richest of the oil shale deposits are located in the Piceance Creek Basin of western Colorado, it is in this region where the first impacts from development will occur.

Technological considerations necessary for extracting oil from these shale deposits has been established for some time, and there have been pilot plants in operation demonstrating the technical feasibility of several different processes. Proposed production schedules suggest the possibility that pyrolysis plants capable of producing an estimated 150,000 to 250,000 barrels of oil per day could be in operation before 1985. Although these estimates are only a fraction of the anticipated full scale development of perhaps two million barrels per day, the impact that facilities of this size could have upon the air quality of the Piceance Basin may be significant. It is important, therefore, to obtain some idea of the carrying capacity of the regional atmosphere.

AIR POLLUTION POTENTIAL

The impact of development upon the air quality of a region depends upon two physical considerations: the amount of contaminant material injected into the air and the dispersive properties of the regional atmosphere.

Regional air pollution potential is determined by the interrelationships between meteorological factors and terrain configuration and is not related to ambient pollutant concentrations or sources within the region.

The air pollution potential is low if effective dispersal of contaminants occurs and conversely, if winds are light and the atmosphere is stable, the potential for air pollution would be greater (Shaw and Munn, 1971).

The worst situation for dispersal can be visualized when both persistent subsidence occurs and snow cover prevents adequate surface heating for the destruction of the radiation inversion for some time.

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In addition to general meteorological conditions, the atmospheric carrying capacity of a specific region depends upon the interrelated factors of large scale climatic controls and local topographic influences upon the microclimate. The large scale climate of western Colorado is controlled by the combined effects of latitude, continentality, elevation, and location with respect to storm tracks. The influence of latitudinal control is exerted primarily through earth-sun geometry. Continentality is a measure of the distance to the nearest ocean controlling the amount of moisture an air mass contains when it reaches a specific region. Western Colorado is far from any major oceanic influence and is therefore subject to air masses which have traveled long distances across the dry intermountain states. Initial moisture from Pacific air masses is removed orographically by the coastal and the Sierra Nevada ranges creating an extensive rain shadow over most of the western states including the Piceance Basin region, and the storm tracks which could bring moisture from the Gulf of Mexico are effectively blocked by the Continental Divide of the Rocky Mountains to the east. In winter, continentality and the locations of these mountain ranges combine to make air masses reaching western Colorado quite dry and seldom severely cold (Marlatt 1973). During winter months the weather patterns are often dominated by large scale high pressure systems characteristic of mid-latitude continental regions. Associated with these high pressure systems are features of stability and subsidence which tend to reduce the dispersive capabilities of the regional atmosphere. A study done by Hosler (1961) indicated that stable conditions occur approximately 40 to 55 percent of the time in fall and winter, and 30 to 40 percent during spring and summer over the western Colorado region.

From an air pollution standpoint, the local topographical influences are also very important. The Piceance Basin is a bowl-shaped depression nearly 1800 km^2 in area which is extensively dissected by Piceance and Yellow Creeks and their tributaries. The two major streams flow northward to intersect the White River flowing westward to join the Green River in Utah. The configuration of the Basin is such that the only channels for cool air flow into the lower valleys are the narrow Piceance and Yellow Creek canyons. When microclimatic influences of calm or light winds and inversion conditions dominate the local weather pattern, air drainage is restricted. The cool dense air under the inversion layer forms deep pools in the lower Basin, and as a result of the stability of these cool air pools, a high potential for air pollution exists.

The combination of the presence of snow cover, a persistent high pressure system over the Piceance Basin, and the restrictions to drainage flow all contribute to the worst possible situation from an air pollution standpoint, that is, when these factors combine to allow the radiation inversion to become established and persist for more than a few hours. Although the frequency and duration of these situations are not well known for the Basin, enough data have been accumulated to show that these conditions indeed do exist across most mid-latitude continental regions and therefore would be expected over the Piceance Basin as well.

Quantification of the frequency and duration of high air pollution potential periods is difficult because the base, as in many remote regions, is severely lacking. Although precipitation and temperature records are available for certain locations in the Basin, long term records of other meteorological phenomena, especially wind speeds, are virtually nonexistent.

Inadequate meteorological data must be augmented by assumptions which do not contradict existing data or physical reality. Since episode or worst case conditions are the most important ones where human health is involved, the meteorological assumptions used in this impact assessment were made to represent such conditions. Light wind speeds were chosen to represent drainage flow conditions. Mixing depths were chosen to represent feasible conditions supported by the limited data available.

CONTAMINANT EMISSIONS ESTIMATES

Once the air pollution potential has been estimated, the remaining requirement which must be satisfied before the impact of oil shale development upon the air quality of the region can be assessed is that of estimating the amount of oil expected to be recovered from this resource in the near future. Knowing this amount and a range of alternative retorting schemes allows estimation of emissions into the atmosphere to be expected from these facilities.

Several techniques have been developed to extract oil from shale and detailed descriptions of these processes are available elsewhere (U.S. Department of Interior, 1973). Emission rates from the TØSCØ retorting process were used in this analysis.

Under ideal circumstances, meteorological data are available and the rates of contaminant emissions are known or can be directly measured. Under such conditions it is possible to monitor the ambient contaminant concentrations to determine directly the impact of a source upon the local air quality by comparing the measured

concentrations to the federal or state air quality standards. Such ideal conditions are the exception, however, especially in remote regions like the Piceance Basin where no previous industrial development has occurred on a scale to significantly affect the ambient air quality. In this region, there had been no reason to monitor the air quality or meteorological conditions until the development of an oil shale industry was assured. Direct measurements of ambient concentrations resulting from industrial activity are precluded in this case since there are no full scale facilities in operation in the Piceance Basin at the present time. Other methods are therefore required in making estimates of the ambient concentrations of pollutants and traditionally these estimates have been made through the use of mathematical models.

The most widely used statistical method of estimating contaminant concentrations from continuous point sources is the Gaussian plume model. In this method, the decrease in concentrations with distance away from the plume centerline is assumed to be due to random, independent particle motion. The resulting contaminant concentration across the plume can therefore be approximately represented by a double normal probability (Gaussian) distribution. Mathematically stated:

$$Pr(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{(x-\bar{x})^2}{2\sigma_x^2} - \frac{(y-\bar{y})^2}{2\sigma_y^2}\right] \quad (1)$$

When meteorological symbols are substituted and the surface is assumed to be a perfect reflector, equation (1) becomes the classic Gaussian plume model (Turner 1970):

$$\chi(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \left(\exp\frac{-y^2}{2\sigma_y^2}\right) \left(\exp\frac{-(z-H)^2}{2\sigma_z^2} + \exp\frac{-(z+H)^2}{2\sigma_z^2}\right) \quad (2)$$

where $\chi(x,y,z)$ is the mass of contaminant per unit volume at (x,y,z); Q is the emission rate; σ_y and σ_z are standard deviations of pollutant concentration distributions in the horizontal and vertical directions, respectively; u is the mean wind speed; x, y, and z are Eulerian coordinates with the origin at the base of the emitting source; and H is the sum of physical height of the stack and plume rise.

In mountainous regions the plume from a continuous point source may be horizontally constrained by local topographic features, vertically trapped by an inversion layer, or effectively restricted by both. When thus restrained, contaminants become uniformly mixed both vertically and horizontally at relatively short distances downwind. Panofsky (1969) used this concept in developing a simplified model where the concentration (χ) varied directly with the emission rate (Q), and inversely with valley width (w), mixing depth (h), and wind speed (U) so that $\chi = Q/whU$. The volume contained by topographic features and the mixing depth is seldom completely sealed, however, but is ventilated through areas where the topography does not reach the height of the inversion layer.

Continuity requires that the time rate of change of mass within the box must be equal to the difference between the mass of pollutants emitted into the box and the mass per unit volume removed through the ventilation areas. In mathematical terms:

$$\frac{dM}{dt} = Q - Vr\,\frac{M}{V} \quad (3)$$

where M is the mass of pollutant, V is the box volume, Q is the emission rate (mass per unit time), Vr is the ventilation rate (ventilating area times wind speed), and M/V is the pollutant concentration (mass per unit volume). Solving for M/V produces:

$$\frac{M}{V} = \frac{Q}{Vr}\left[1-\exp\left(-\frac{Vr}{V}t\right)\right] + \frac{M_0}{V}\exp)-\frac{Vr}{V}t) \quad (4)$$

where M_0 / V is the existing concentration at t = 0.

The assessment of the impact on air quality involves methods combining both the air pollution potential which occurs under certain meteorological conditions and an inventory of contaminant emission rates to produce estimates of the ambient contaminant concentrations. Ambient concentrations were calculated using equations (2) and (4). The results were compared with applicable state and federal air quality standards.

AIR QUALITY STANDARDS

Known or suspected adverse effects depend upon certain levels of concentration and exposure times. The descriptions or technical statements of the effects of a pollutant under various conditions are called the air quality criteria for the pollutant. Air quality goals are even more encompassing and represent levels of concentrations below which no adverse effects are known to occur. Neither criteria nor goals have legal significance, however, but are important steps in the development of air quality standards. The 1970 Amendments to the Clean Air Act required the Environmental Protection Agency Administrator to establish primary and secondary air quality standards. Primary standards, based upon criteria as

defined above, were to be designed to protect the public health. Secondary standards, based upon air quality goals, were to be designed to protect the public welfare. The Administrator set federal primary and secondary air quality standards and most states have developed their own standards. Many states, in fact, have developed standards more stringent than national ones. These established standards become guidelines to which existing or projected contaminant concentrations may be compared. Those standards applicable to the Piceance Basin are provided in Tables 1 and 2.

RESULTS AND CONCLUSIONS

The assessment of the impact on air quality under episode conditions requires a comparison between the expected pollutant concentrations and the appropriate air quality standards. The federal or state standards applicable in this case are the primary air quality standards for an averaging time of 24 hours. These standards are not to be exceeded more than once per year. Colorado standards are separated with respect to designated and non-designated areas, and the Piceance Basin is classified as a non-designated area.

The Colorado, non-designated area, 24 hour maximum standard of 15 $\mu g\ m^{-3}$ is the most stringent of the sulfur dioxide standards. Results from the box model show that a concentration of nearly 46 $\mu g\ m^{-3}$ might be expected under conditions of a 305 meter mixing depth persisting for 24 hours. Stated differently, continuous operation of two retorting facilities each with a daily output of 50 thousand barrels beneath an inversion of 305 meters for 24 hours would create sulfur dioxide concentrations exceeding the Colorado standard by 300 percent. This standard would preclude any development of oil shale in the Piceance Creek Basin. The federal standard, by comparison, would allow a daily output of 400 thousand barrels or 8 plants, each with a daily output of 50 thousand barrels under similar conditions. If the average mixing depth of 458 meters were to persist for 24 hours, the Colorado sulfur dioxide standard would be exceeded by 135 percent. The federal standard would allow a daily production rate of 900 thousand barrels or 18 facilities producing at a daily rate of 50 thousand barrels. The federal 3 hour secondary standard of 1300 $\mu g\ m^{-3}$ will probably not be exceeded in the Piceance Basin if the TØSCØ process is used.

A three hour averaging time federal standard also exists for total hydrocarbons (160 $\mu g\ m^{-3}$), but concentrations of this magnitude are not expected to occur in the Basin provided the TØSCØ process is used. Sulfur dioxide production from processes other than TØSCØ is estimated from one to ten times greater, and hydrocarbon production from other processes is estimated to be three to four orders of magnitude greater than the TØSCØ process. If schemes other than the TØSCØ process were to be used, a reassessment would be necessary with respect to total hydrocarbons and sulfur dioxide. No federal or state 24 hour standard exists for oxides of nitrogen. Production of these oxides is dependent upon combustion temperature and therefore is highly variable. Oxides of nitrogen and hydrocarbons may combine to form photochemical smog in the presence of sunlight. This could become a problem if other processes of oil extraction are used, but no standards have been developed pertaining to combinations of pollutants emitted into the atmosphere.

Calculated concentrations of particulates are somewhat misleading as a result of the initial assumption that pollutants are not removed from the atmosphere by deposition. No size distribution was provided in the emissions data and therefore the total amount was assumed to be suspended. This would not be the case in reality, but without size distributions, the amount suspended cannot be realiably estimated. With this limitation disregarded, the Colorado non-designated area standard for particulates of 45 $\mu g\ m^{-3}$ would limit the production of oil to a daily rate of approximately 68 thousand barrels under conditions of a 305 meter mixing depth which persists for 24 hours. The federal primary standard for particulates (260 $\mu g\ m^{-3}$) would allow a daily production rate of nearly 400,000 barrels . The federal secondary 24 hour standards, however, would limit the amount to less than 230,000 barrels per day.

As the mixing depth approaches the maximum elevations of the Piceance Creek Basin, more of the contaminated air becomes entrained into the synoptic flow and the production rate of oil shale facilities could increase to very high values without violating established ambient air quality standards within the Basin. Pollutants from the maximum feasible development, however, will have an unknown impact upon the environment beyond the Piceance Creek Basin.

SUMMARY

Even though data are severely limited or nonexistent, it is nevertheless reasonable to conclude that high potential for air pollution episodes exist in the Piceance Creek Basin of western Colorado. It is much more difficult to reach conclusions regarding the actual impact on air quality to be expected from proposed development of the oil shale industry. This difficulty is related to uncertainties in predicting which of the retorting techniques are to be used, in addition to the broad range of estimates of the size and number of facilities

TABLE 1. FEDERAL AIR QUALITY STANDARDS

Units are in $\mu g\ m^{-3}$.

Substance	Federal air quality standard	
	Primary	Secondary
Particulate		
annual geometric mean	75	60
24 hour maximum*	260	150
Sulfur oxides		
annual arithmetic mean	80	--
24 hour maximum*	365	--
3 hour maximum*	--	1300
Oxidant		
1 hour maximum*	160	160
Hydrocarbons		
3 hour maximum* (from 6 to 9 A.M.)	160	160
Carbon monoxide		
8 hour maximum*	10,000	10,000
1 hour maximum*	40,000	40,000
Nitrogen oxides		
annual arithmetic mean	100	100

*Not to be exceeded more than once per year.

TABLE 2. Colorado air quality standards. The Piceance Creek Basin is classified as a "non-designated area" and therefore the "designated area" standards are not applicable. Standards for oxidant, hydrocarbons, and carbon monoxide are shown even though these standards apply only to the Denver Air Quality Control Region as noted. There is currently no Colorado standard for nitrogen oxides. The standards shown in this table are currently subject to revision. Units are in $\mu g\ m^{-3}$.

Substance	Colorado Air Quality Standards			
	Non-designated Area	Designated Area		
		1973	1976	1980
Particulate				
annual arithmetic mean	45	70	55	45
24 hour maximum*	150	200	180	150
Sulfur oxides				
annual arithmetic mean	-	60	25	10
24 hour maximum*	15	300	150	55
1 hour maximum*	-	800	300	-
	Proposed Denver Air Quality Control Region			
Oxidant				
annual				
8 hour maximum*				
1 hour maximum*				
Hydrocarbons				
annual				
8 hour maximum*				
1 hour maximum*				
Carbon monoxide				
annual				
8 hour maximum*				
1 hour maximum*				

*Not to be exceeded more than once per year.

**Not to be exceeded more than once per month.

to be in operation in the near future. Further uncertainty is associated with the boundary conditions, assumptions, and extrapolations which may be violated or wrongly applied when using mathematical air pollution models. The limitations of this study, although many, are inherent in any attempt to determine the impact of projected industrial development upon the environment of a remote region before such development occurs. In the Piceance Creek Basin, under the assumptions that the TØSCØ process is used in facilities capable of producing 50 thousand barrels of oil per day, and assuming that the drainage winds are 2 m sec^{-1} beneath an inversion layer 305 meters (1000 feet) above the surface, the Colorado sulfur dioxide standard of 15 $\mu g\ m^{-3}$ would be exceeded by 300 percent, while the federal standard of 365 $\mu g\ m^{-3}$ would allow daily production of 400 thousand barrels. Under similar conditions, the federal secondary 24 hour particulate standard and the Colorado non-designated 24 hour particulate standard (both 150 $\mu g\ m^{-3}$) would limit the daily oil production rate to less than 230 thousand barrels.

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An Air Quality Index to Aid in Determining Mountain Land Use[1]

Michael A. Fosberg and Douglas G. Fox[2]/

Recently developed modeling techniques allow planners to incorporate air quality into land use plans early in the planning activity. A wind-field model was combined with dispersion models to determine a mixing volume. This mixing volume contains no source information, so planners would use a spatial matrix of the index as an input constraint in land use plans. Allowable emissions are calculated from the mixing volume index and the ambient air quality standards. These allowable emissions for each pollutant form an atmospheric constraint matrix for air pollution that is compatible with economic, social, and other models in land use planning.

INTRODUCTION

There has been a longstanding need to incorporate air quality constraints at an early stage in land-use planning activities. Traditionally, there has been no direct feedback or air quality information until after plans were somewhat formalized. Then, air quality would be evaluated as a residual calculation.

Non-degradation requirements set by the Environmental Protection Agency (Code of Federal Regulations 1975) require that all areas of the country be classified in areas in which no degradation is permitted (Class I), areas in which some degradation is permitted (Class II), and areas which allow air quality up to the primary standards (Class III). Because of these regulations, an air quality index that defines a carrying capacity or mixing volume of a geographic region, and permits preselection of desired air quality, is required. This air quality index should reflect only meteorological constraints. Emissions from planned activities could then be evaluated against this index to define projected air quality, or conversely if desired air quality is to be predefined, the index could be used to determine the intensity and kinds of development, in terms of allowable emissions.

THE PLANNING INDEX

The Pollutant Standards Index (PSI or Ψ) has been proposed (Thom and Ott 1976) as a universal air quality index that facilitates comparison of air quality levels at different locations, and provides policymakers with a uniform measure for evaluating impact of regulations. The Pollution Standards Index is defined as a segmented linear function, where an index value of 100 is air quality at the Primary National Ambient Air Quality Standard, and an index of 50 is at the secondary standard, if a secondary standard exists. If no secondary standard is defined, then an index of 50 is half the primary standard. While the primary standards are set on the basis of human health, the secondary standards are designed to protect welfare, specifically to protect vegetation and materials. The PSI is defined as:

$$\Psi = a + b \frac{\chi}{\chi_s} \qquad (1)$$

Where χ is the ambient concentration, χ_s is the primary standard, and

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the coefficients a and b are 0 and 100 respectively for SO_x, NO_x, CO and hydrocarbons.
For particulates, a = 0 and b = 87 for concentrations up to the secondary standard and a = -19 and b = 119 for concentrations between the secondary and primary standards.

Pollutant Standards Index values greater than 100 are not of interest to planners since these values exceed the National Ambient Air Quality Standards.

The actual concentration, χ , can be estimated from dispersion models. For simplicity, consider the mixing volume index as defined by the Gaussian dispersion model for complex terrain (Fosberg, et al. 1976). The concentration, χ in $\mu g/m$, is given by

$$\chi(x) = \frac{Q}{u} G(x) \qquad (2)$$

where

Q = emission rate in $\mu g/sec$
u = mean velocity in m/sec
$G(x)$ =

$$\frac{1}{\sqrt{2}\,\pi\sigma_y\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^{\,2}} + \frac{z^2}{\sigma_z^{\,2}}\right)\right] \exp(-\delta\Delta\tau)$$

where

$\sigma_y = \sigma_y(x)$ is the standard deviation of of the pollution cloud in the lateral direction determined by Pasquill-Gifford curves (Turner 1969)(m)
$\sigma_z = \sigma_z(x)$ is diffusion in the vertical (m)
δ = mass divergence of the airshed in sec^-
$\Delta\tau$ is the time increment over which the divergence acts (sec).

A mixing volume index can be defined from this formulation as

$$I = \frac{\chi}{Q} 10^6 = \frac{G(x)}{u} 10^6 \qquad (3)$$

The scaling factor, 10^6, was chosen by considering Turner's (1969) maximum value of $\chi u/Q$ for a ground level source with class F stability. This scaling gives a maximum index value of 1000, although the index values will typically be one or two orders of magnitude smaller. The index, I, contains only climatological information and has the advantage that it can be mapped over broad areas so that the planner need not be concerned with detailed dispersion processes.

A land use planning index can be formed by combining the Pollution Standards Index, Ψ , (eq. 1) with the Mixing Volume Index, I, (eq. 3). The ambient concentration is eliminated between the two equations, with the result that

$$\frac{QI}{10^6} = \frac{(\Psi - a)\,\chi_s}{b} \qquad (4)$$

Rearranging eq. 4 to solve for Q, a Pollution Index (PI or π) is formed which defines the maximum allowable emission in terms of mixing conditions, air quality standards and the nondegradation classification. The PI is simply the total allowable emission given as,

$$PI = Q = \frac{(\Psi - a)\,\chi_s\, 10^6}{b\, I} \qquad (5)$$

The emission term Q can be generalized to include multiple sources of a given pollutant through

$$\Sigma_i\, n_i\, Q_i = PI \qquad (6)$$

where n_i is the number of sources for a particular activity and Q_i is the emission rate for that activity.

The emission used in eq. (1) must be uniform in order for the Gaussian solution to be correct. Strictly the index (eq. 3) can be used to describe concentrations that result from a uniform emission. This is most appropriate for short times (one to three hours), where u does not vary substantially nor do the stability classes needed to determine the σ_y and σ_z values.

For longer times (24 hours) however, it is more appropriate to base concentration in a mountain valley complex on the concept of a box model. The total mass of pollution is assumed to be emitted into a volume described by an area of limited horizontal extent, topped by a low inversion. This type of calculation can be made using the index defined in eq. (3) if the Gaussian is evaluated at a downwind distance X_L sufficiently large that the cross-sectioned area approximates a valley cross-section. Details of this derivation are found in a companion paper (Fosberg and Fox 1976) which provides the theoretical development of these concepts.

The PI index for a box model is written as,

$$PI = \Sigma_i n_i Q_i \Delta t_i = \frac{9(\Psi - a)\, X_L\, \chi_s 10^6}{2\, b\, I\, u} \qquad (7)$$

Where again X_L represents the distance at which the concentration distribution approximately fills the appropriate cross-section.

A LAND USE PLANNING EXAMPLE

In order to illustrate how this technique would work in practice, we will use a wind field determined from a model of the wind over complex terrain (Fosberg, Marlatt and Krupnak 1976) and calculate the mixing volume index for each 3 km square grid cell. As a less involved method of calculating, I could employ data such as Holzworth's mixing depths (Holzworth 1972) and topography maps to estimate volumes. Mixing volume index values developed from either approach contain only information on dispersion potential.

For the purpose of this example we will use the wind field shown in figure 1. The area depicted in this example is in southwestern Montana. Meteorological conditions are chosen to be those which could lead to a high pollution period during a summer evening. As a specific example, consider the development of a 26,700 acre mountain subdivision. Our analysis is based upon 12 3 km square grid cells which cover the area. The primary sources of pollution will be fireplaces and automobiles. We assume that the State has classified the subdivision within an air quality maintenance area having a Class II designation. Particulate concentration in a Class II area cannot exceed 30 μ g/m in a 24-hour period, or a $\Psi = 11$. Using the box model version of the Pollution Index, we solve eq. 7 to determine the number of fireplaces that can burn simultaneously,

$$PI = \sum_i n_i Q_i \Delta t = \frac{(\Psi - a) X_s 9 X_L 10^6}{2\ b\ I\ u}$$

where

Ψ = 11

a = 0

X_s = 260 g/m

X_L = 3000 meters

b = 87, and

I and u are determined for each cell from the flow field (u) and eq. 3, the mixing volume index.

The number of fireplaces or homesites with fireplaces is then

$$n = \frac{P\,I}{Q\,\Delta t}$$

We assume that fireplaces are burning for two hours (Δt = 2 hr.) and the emission, Q = 7.5 X $10^7 \mu$g/hr. is given by a recent EPA report (Snowden 1976). The number of fireplaces, n, in this tract is calculated for each of the 12 cells. Number of homesites per cell range from a low of 17 to a high of 50 giving a total of 441 for the entire tract. Thus the proposed subdivision must allot an average of 60 acres for each homesite. If the area were allowed to reach the National Ambient Air Quality Standards, 3970 homesites of 6 acres each could have been developed. This average acreage includes common and non-developable property such as roads, parks, lakes, and so forth. Using similar procedures we could include emissions of CO, and calculate the allowable number of vehicles. It should be emphasized here that these calculations are for episode situations and not for typical meteorological conditions.

SUMMARY

The Pollutant Standards Index and the mixing volume index provide land planners with quantitative estimates of the number and type of emissions permitted in an area. The Pollutant Standards Index provides for a uniform interpretation of land use regulations while the mixing volume index relates these regulations to any meteorological limitations. The procedure allows the calculation of instantaneous pollution concentration using the Gaussian model concept (eq. 5) as well as the calculation of long term pollution, or pollution from intermittent sources using the box model (eq. 7).

The mixing volume index and the Pollutant Index provide planners with quantitative estimates of the allowable number of emission sources in a mountain valley. They allow the planner to quantitatively determine the mix of and amount of different activities contributing a particular pollutant to the air shed. Thus they provide the carrying capacity of the air shed for pollution and can be encorporated into other forms of planning models for general use.

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Session VII

Influence of Atmospheric Pollutants on Biological Systems

Chairman: Dr. J. S. Krammes

Forest Environment Research Staff

United States Department of Agriculture

Washington, D. C.

The Changing Chemistry of Precipitation and Its Implications for Forest Growth and Productivity[1]

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Abstract.--The nutrient status, growth and reproduction of plants on land and in surface waters is influenced by the availability of beneficial nutrient elements and potentially injurious substances dispersed in the atmosphere. In recent decades, human activities have greatly increased total emissions and deposition of substances from the atmosphere. A network of precipitation-measuring stations has existed in Europe since 1947 and has provided much insight into atmospheric chemistry and the effects of atmospheric trace constituents within terrestrial and aquatic ecosystems. The chemistry of precipitation also has been studied in certain parts of the United States and Canada. The results of these studies are described together with plans for development of a coordinated network to measure changes in the chemistry of atmospheric deposition and its effects on vegetation and surface waters in the United States and Canada.

ESSENTIAL ELEMENTS FOR GROWTH OF FOREST TREES

Fifteen elements are essential for the growth of forest trees (Table 1). Previously, it was believed that these elements were obtained almost entirely from the soil solution after release from decomposing organic matter, weathering of soil minerals, or addition as fertilizers. Now, it is recognized that air-borne gases, particulate matter, and aerosols significantly augment the supply of both essential elements (Tamm, 1958) and potentially injurious substances (Wood, 1968; Mudd and Kozlowski, 1975). Furthermore, all of the 15 essential elements listed in Table 1 can be taken up through foliar organs as well as by absorption from the soil solution (Wittwer and Bukovac, 1969).

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Table 1.--Essential elements for growth of forest trees

Elements	Distribution	Availability
Carbon Hydrogen Oxygen	All organic compounds esp. cellulose, hemi-celluloses and lignin	Rarely limiting
Nitrogen	Proteins, amino acids, nucleic acids, etc.	Usually limiting
Phosphorus	Nucleic acids, ATP, phospholipids, etc.	Often limiting
Potassium	Growing portions	Often limiting
Sulfur	Proteins	Sometimes limiting
Ca, Mg	Pectic substances	Rarely limiting
Fe, Cu, Mn, Mo, Bo, Zn	Cofactors or constituents of enzymes or cytochromes	Rarely limiting

Table 2 lists the major inputs and losses of nutrients from a forest ecosystem. Rennie (1955) has shown that much larger amounts of essential nutrients are required for sustained-yield agriculture than for sustained yield hardwood or softwood forestry. This is true because the part of trees that usually is harvested -- the wood and bark of the tree stem -- contain very much less of most essential elements than the seeds and other plant parts that are commonly harvested in agriculture. This is a

major reason why fertilization is so commonly practiced in agriculture but is much less common in forestry. In some forested regions, atmospheric deposition alone is more than adequate to permit harvesting of crop after crop of trees without fertilizing the forest.

Table 2.--Nutrient flux in a forest ecosystem

Addition of nutrients	Loss of nutrients
1) Precipitation	1) Air-borne pollen and spores
2) Salt spray from oceans	2) Harvesting of forest products
3) Wind-borne dust, soil particles, aerosols	3) Leaching from forest soils to ground water
4) Atmospheric gases: CO_2, NH_4OH, N_2, SO_2	

SOURCES AND AMOUNTS OF ATMOSPHERIC DEPOSITION

In recent decades, human activities have greatly increased total emissions and deposition of substances from the atmosphere (Oden, 1968, 1976) (Bolin, et al 1971). This is due mainly to increases in: 1) combustion of fossil fuels in industrial enterprizes, residential heating, transportation, and agricultural operations; 2) use of fertilizers and other chemicals in intensive agriculture; and 3) decomposition of industrial, urban, and agricultural wastes. Previously, it was believed that most of these materials were removed from the atmosphere near the site of emission. Now it is recognized that atmospheric processes can lead to extensive mixing, and both chemical and physical interactions and transformations of atmospheric particles, aerosols and gases. Furthermore, these substances and their reaction products are dispersed by meteorological processes and finally enter the biosphere in fields of deposition that may extend hundreds or even thousands of kilometers from the original sources of emission. The recent fallout of radioactive substances in the eastern United States as a result of atomic explosions in the Peoples Republic of China provides a dramatic reminder of long-distance transport and deposition of pollutants. Thus, the chemical composition of atmospheric deposition within a given region is a function of all the airborne substances dispersed, mixed, transformed, and transported into the atmosphere of that region and then deposited in terrestrial and aquatic ecosystems (Dovland et al, 1976).

Forest, agricultural, and aquatic biologists are becoming increasingly concerned about atmospheric transport and deposition of both nutritionally beneficial and potentially injurious substances. This is true because: 1) vegetation, soils, and surface waters are the primary deposition sites for precipitation and airborne particulate matter of all types; 2) atmospheric deposition constitutes an important source of nutrients and potentially injurious substances that effect the productivity and stability of these ecosystems; and 3) human activities are steadily increasing the amounts and variety of substances present in atmospheric deposition.

The amounts of various substances introduced deliberately or inadvertently by man into the biosphere of the earth are becoming so large that man is becoming a major force in the biogeochemistry of the earth (Kovda, 1975). This is shown in Table 3 which contains a tabulation of data on annual output of fertilizers, industrial dusts, garbage and other urban wastes and by products, mine refuse, and discharges of aerosols and gases. All of these categories of matter are becoming comparable in magnitude with the discharges of dissolved and suspended substances in all the rivers of the world, the annual yield of photosynthetic products, or the cycling of inorganic elements in the earth as a whole. Anthropogenic emissions into the atmosphere are also very large as shown in Table 4.

Table 3.--Biogeochemical and technological forces in the biosphere of the earth (data of Kovda, 1975)

Biosphere components	Tons per year
Biogeochemical processes:	
Yield of photomass	1×10^{10}
Cycle of inorganic elements	1×10^{10}
River discharges:	
Dissolved substances	3×10^{9}
Suspended substances	2×10^{10}
Anthropogenic sources:	
Output of fertilizers	3×10^{8}
Industrial dust	3×10^{8}
Garbage, urban wastes and byproducts	2×10^{10}
Mine refuse	5×10^{9}
Aerosols and gas discharges	1×10^{9}

Table 4.--Anthropogenic emissions into the atmosphere (data of Kovda, 1975)

Type of emission	Tons per year
Dust	2.5×10^{8}
Gases (mainly SO_2, HC, and NO_x)	6.5×10^{8}
Carbon oxides ($CO + CO_2$)	2.0×10^{9}
Aerosols	1.0×10^{9}

Note: Doubling about every 7-10 years

If man is to so greatly augment the amounts of substance dispersed in the atmosphere and deposited into the biosphere of the earth, it is prudent (no essential!) that he should measure the amount and chemical form of the deposited matter and understand the biological consequences of that deposition. Regretably, our understanding of these processes in North America is fragmentary. Fortunately, however, more extensive measurements of atmospheric deposition and its biological consequences have been made in Europe where an atmospheric chemical network has been maintained since the late 1940's.

THE ATMOSPHERIC CHEMICAL NETWORK IN EUROPE

The first regional Atmospheric Chemical Network began in Scandinavia and has gradually spread to include most of western Europe and parts of eastern Europe including Poland and the Soviet Union. The substances analyzed at most of these stations include the following major cations and anions: NH_4, NO_3, PO_4, K, Ca, Mg, SO_4, Na, Cl as well as pH, conductivity, and titratable acidity and alkalinity.

Fig. 1 shows some long-term trends in amounts of nitrate nitrogen deposited at five locations in Europe. It is obvious that the amount of this important fertilizer element in precipitation changed markedly (generally increased) during the 15 years between 1955 and 1970. Nitrate nitrogen helps plants grow. Thus, the nitrogen added in precipitation would be expected to increase yields of agricultural and forest crops.

But not all the substances in precipitation are beneficial. Long term trends also have been detected in amounts of sulfate and hydrogen ions. Fig. 2 shows the trend in pH in six specific locations in Norway and Sweden. These changes have been attributed to strong acids formed in the atmosphere, mainly from oxides of sulfur and nitrogen produced during combustion of fossil fuels (Bolin et al, 1971). At present about two-thirds of the total acidity in rain and snow in Scandinavia and the northeastern U.S. is due to sulfuric acid and most of the remainder is due to nitric acid (Likens et al, 1976; Dovland et al, 1976).

In interpreting the data of Figs. 1 and 2 it is important to recognize that precipitation formed in an atmosphere relatively free of natural or anthropogenic sources of nitrogen or sulfur oxides would be expected to have a pH of 5.5-6.0 (Likens and Bormann, 1974; Dovland et al, 1976). Since pH is a logarithmic scale, a change in hydrogen ion concentration from pH 6.0 to pH 4.5 means a 32-fold increase in acidity.

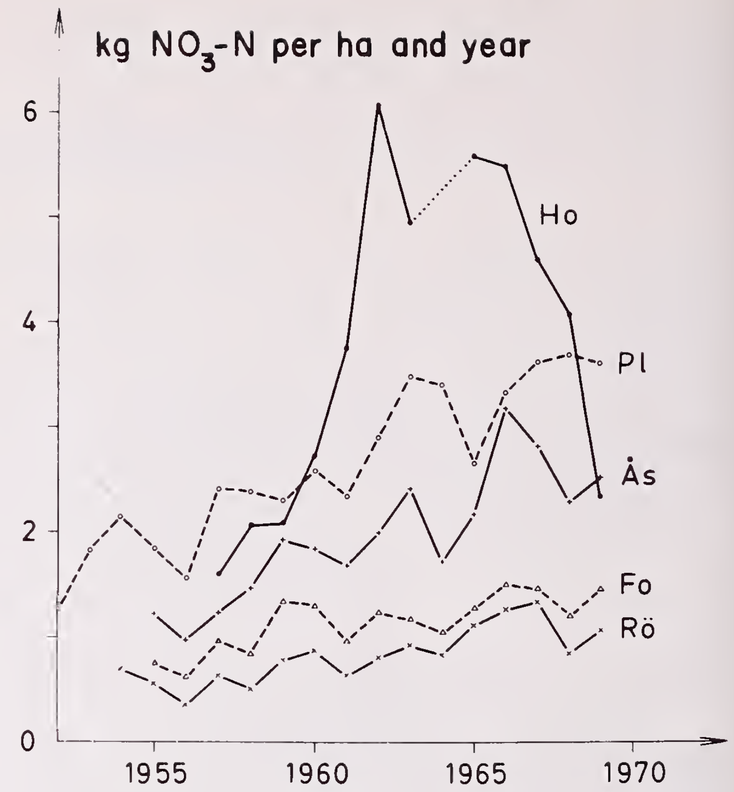

Figure 1.--Amount of nitrate nitrogen (1 kg/ha = about 1 pound/acre) deposited in precipitation at five locations in northern Europe during 1955-70. The station designated Ho is in West Germany, those designated Pl, Fo, and Rö are in Sweden, and the station designated Ås is in Norway. (Data of Oden, 1968).

PRECIPITATION CHEMISTRY IN THE UNITED STATES

Monitoring of the chemistry of precipitation also has been carried on in the United States (Feth et al, 1964; lodge et al, 1968). Figure 3 shows some data that are typical of American monitoring studies: (1) The data were collected for a limited land area -- in this case parts of North Carolina and southeastern Virginia; and (2) the data were collected for a limited period of time (1962-63)(Gamble and Fisher, 1966). These data are very detailed and provide excellent and reliable information. But the study terminated in July 1963 and monitoring has not been done in the same area until very recently. The Hubbard Brook Experimental Forest in New Hampshire is the only site in the U.S. where the acidity of precipitation has been measured consistently for as long as 10 years.

Using measurements of precipitation chemistry in limited areas and periods of time, and assuming a stoichiometric balance between anions and cations in precipitation, Cogbill

and Likens (1974) calculated the probable average acidity of precipitation in the eastern United States.

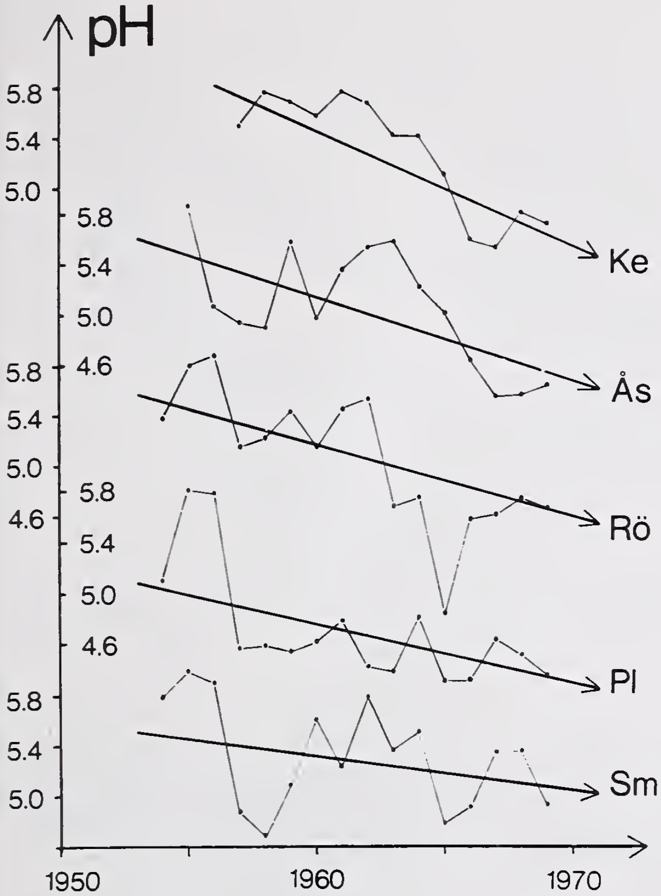

Figure 2.--Average acidity of precipitation collected at six locations in Scandinavia during 1965-79. The stations designated Ke and Ås are in Norway; those designated Rö, Pl and Sm are in Sweden. (Data of Oden, 1968).

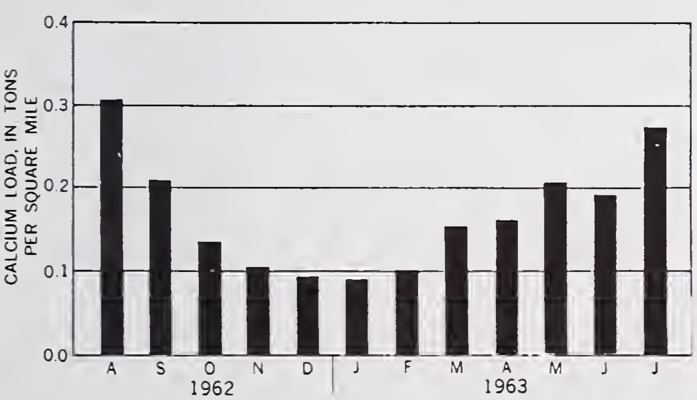

Figure 3.--Amount of calcium deposited in precipitation in parts of North Carolina and Virginia during 1962-63. (Data of Gambell and Fisher, 1966).

As shown in Figure 4 precipitation in a large portion of the eastern United States was less than pH 5.6 in 1955-56; the zone of greatest acidity (lowest pH) was generally consistent with the zone where sulfur emissions are high -- parts of Ohio, Pennsylvania, West Virginia, New York, and New England. By 1965-66, the zone with an estimated pH of 5.6 had continued to expand although the zone with a pH of less than 4.5 had not expanded greatly (Fig. 5). Note, however, that a new isopleth line of pH 4.4 is visible. By 1972-73, the area with an average pH of rain below 4.5 had extended to include parts of Mississippi, Alabama, Georgia, South Carolina, North Carolina, Kentucky, Virginia and further north into New England and Canada. Essentially, it embraces most of the area east of the Mississippi River (Fig. 6). Individual rainstorms with pH values between 2.1 and 3 have been reported in various locations -- in some cases many hundreds of kilometers from major sources of air pollution (Likens and Bormann, 1974).

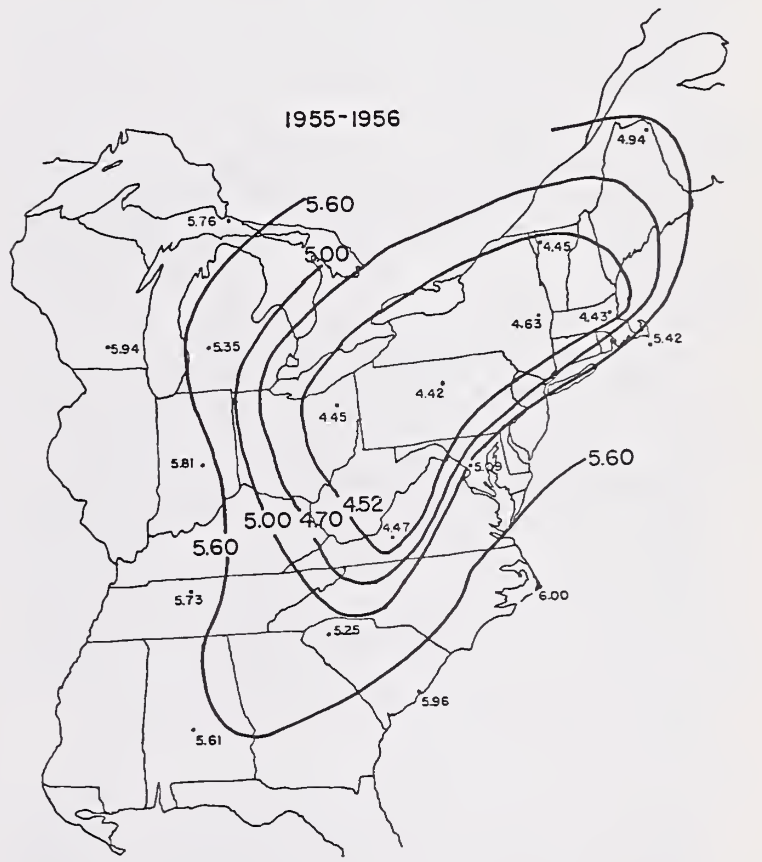

Figure 4.--Distribution of estimated acidity in precipitation in the eastern United States during 1955-56. (Data of Cogbill and Likens, 1974).

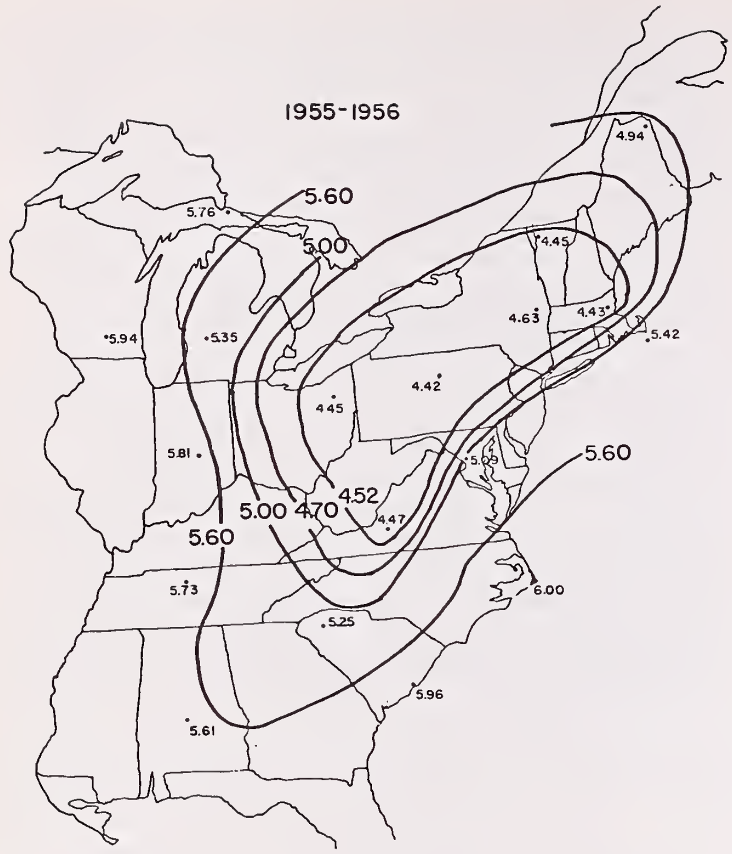

Figure 5.--Distribution of estimated acidity in precipitation in the eastern United States during 1965-66. (Data of Cogbill and Likens, 1974).

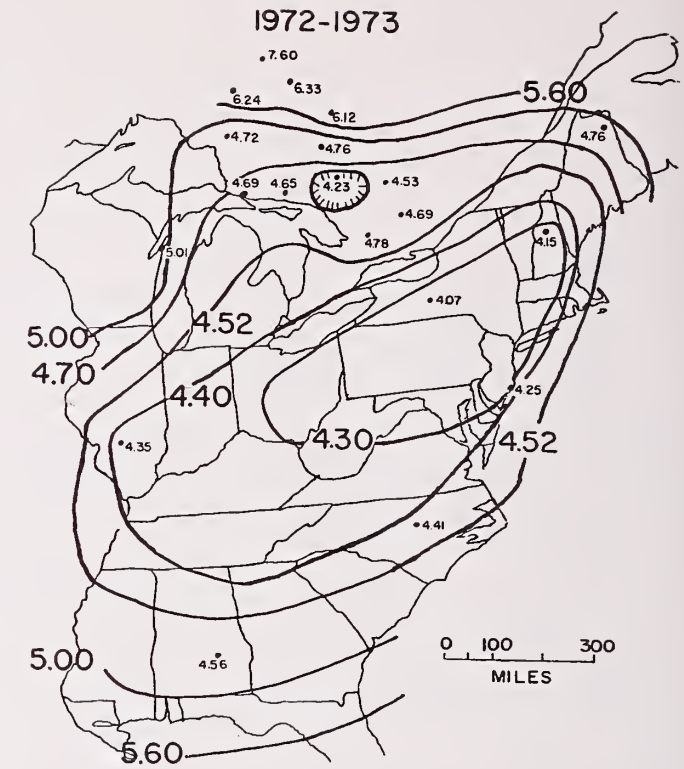

Figure 6.--Distribution of estimated acidity in precipitation in the eastern United States during 1972-73. (Data of Cogbill, 1975).

EFFECTS OF ACIDIC PRECIPITATION IN TERRESTRIAL AND AQUATIC ECOSYSTEMS

A great variety of effects of acidic precipitation on terrestrial and aquatic ecosystems were reported at two recent meetings: the First International Symposium on Acidic Precipitation and the Forest Ecosystem held at The Ohio State University in Columbus (Forest Service, 1976), and an International Conference on the Effects of Acid Precipitation sponsored by the Norwegian Ministry of the Environment held at Telemark, Norway (Braekke, 1976).

The most striking effects reported at these meetings were on populations of fish and other fresh water organisms (Giessing et al, 1976; Gorham, 1976). Dr. Carl Schofield (1976), an aquatic ecologist at Cornell University summarized these effects as follows:

> "Rapid extinction rates of fish populations inhabiting acidified waters have been observed over the past few decades in the Scandinavian countries and parts of eastern North America. Documented case studies of several populations clearly indicate that extinction is often a result of chronic reproductive failure due to acidification-induced effects on sensitive life-history stages."

Effects on soils and on forest vegetation generally have been less clear cut; but certain definite effects have been reported (Abrahamsen, et al 1976; Forest Service, 1976). The most striking of these was development of peat moss (Sphagnum sp.) as a submarine rather than a terrestrial plant in acidified lakes and streams in Sweden (Grahn et al, 1974). Dense mats of Sphagnum and an apparently parasitic aquatic fungus develop on the bottom of these lakes in water as deep as 18 meters. This growth induces oligotrophication (opposite of eutrophication) -- a self-accelerating process that leads to a substantial nutrient impoverishment of lake waters. Analyses of forest growth in southern Sweden from 1896 to 1965 showed a 2 to 7% decrease in growth between 1950 and 1965. Jonsson and Sundberg (1972) "found no good reason for attributing (this) reduction in growth to any cause other than acidification." Similar attempts to quantify possible effects on growth of forests in the United States have been inconclusive.

Other reports given at the meetings in Ohio and Norway indicate that: 1) forest canopies filter out sulfur and hydrogen ions from precipitation; 2) acidity of bark and development of cuticular features such as frequency and size of stomata can be used as biological indicators of acidification and sulfur pollution, respectively; 3) vegetation developing in recently formed sandy soils or glacial outwash areas is more vulnerable to the effects of acidic precipitation than vegetation growing in older, well-buffered soils of high clay content and consequently large base exchange capacity; 4) before reaching the soil, acidic substances in precipitation can induce direct changes in the physiology of foliar organs; 5) after reaching the soil, these substances also can induce changes in root function and the availability of essential cations; and 6) ammonia combines with sulfate ions in the atmosphere and tends to neutralize atmospheric acidity -- when the ammonia is absorbed by plants, however, both the ammonia and the released sulfate ions contribute to the total acidification of forest ecosystems.

Simulated "rain" acidified with sulfuric acid has been reported to: 1) induce direct injury to foliage of pines, birch and mosses; 2) induce symptoms similar to those caused by certain other pollutants and biotic pathogens; 3) induce poorer germination of spruce seeds; 4) accelerate leaching of nutrients from foliage of various angiosperms; 5) increase erosion of epicuticular waxes on oak and bean leaves; 6) decrease uptake of nitrogen by endomycorrhize of sweetgum seedlings; 7) inhibit reproduction of root-knot nematodes; 8) inhibit development of bean rust and production of telia by the oak-leaf-rust fungus, Cronartium fusiforme; 9) inhibit or stimulate development of halo blight in bean seedlings depending on the time in the disease cycle during which the simulated "rain" was applied; and 10) inhibit nodulation and fixation of nitrogen by Rhizobium in bean and soybean seedlings (Shriner, 1976).

Some differences of opinion about the effects of acidification also have become evident. These concern such matters as: 1) the pH of rain formed in a "clean" atmosphere; 2) the balance between nutritionally beneficial and injurious influences of sulfur and nitrogen compounds in precipitation; and 3) the likelihood of negative influences on growth of plants in well-buffered soils.

The possible economic consequences of the various biological effects listed above are not known. Nevertheless, the variety of biological influences that have been observed suggests that: 1) a network to measure long-term changes in the chemistry of air and precipitation is needed in rural and urban areas throughout North America; and 2) much more research is needed to evaluate the ecological and possible economic influences of changes in the acidity and other chemical properties of precipitation.

THE NEED FOR AN ATOMPSHERIC CHEMICAL NETWORK IN NORTH AMERICA

As indicated above, the chemistry of atmospheric deposition has been measured in certain parts of the United States and Canada. But the sampling stations usually have been concentrated in localized regions or have been so relatively few-and-far between that regional and temporal trends have been difficult to discern. When intensive sampling has been accomplished, the data have been collected over relatively short periods of time.

The U. S. Geological Survey (USGS), the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the International Biological Program (IBP), the U. S. Environmental Protection Agency (USEPA), and the Canadian Atmospheric Environment Service (CAES) all have established deposition-measuring systems from time to time. But each of these systems has been relatively short lived. The latest efforts are by the CAES and by the USEPA in cooperation with NOAA. The latter two agencies established a national network which include the 10 U. S. sites of the World Meteorological Organization (WMO). The U. S. joined the WMO Network in 1972. None of the 17 sampling stations included in the U. S. network includes a calibrated watershed where precipitation data has been collected in the past. Furthermore, the collector currently being used is of a type which has been found least satisfactory among more than 12 different designs tested for NOAA (Galloway and Likens, 1975) (Berry et al, 1975).

The relatively short life of atmospheric chemical networks in the United States contrasts markedly with the longevity of the European Atmospheric Chemical Network. The success of the European network has been attributed to five major factors: 1) simplicity in the design of the deposition collector and the shipping and measuring systems; 2) low cost of the central analytical laboratory; 3) coordination of all phases of network operation by a dedicated group of scientists who concerned themselves with all aspects of network operation from choosing the collection sites to final interpretation and publication of the results; 4) continuity in sample collection; this was assured primarily by personal contacts among

scientists who were committed to discovering changes in the chemistry of atmospheric deposition and their ecological effects; and 5) availability of the data to all scientists who wished to use the data.

During the past year, a major cooperative effort involving many different agencies in the United States and Canada has been made to develop a more adequate, long-term regional or national network. The initiative for this effort has been taken by personnel of the State Agricultural Experiment Stations of the Cooperative State Research Service and the Forest Service within the U. S. Department of Agriculture. Other agencies which have indicated an interest in this endeavor include the Agricultural Research Service (ARS), the U. S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), the Energy Research and Development Administration (ERDA), the Environment Protection Agency (EPA), the Canada Atmospheric Environment Service (CAES), the Canada Monitoring and Surveys Division (CMSD), the Sulfate Regional Experiment (SURE) of the Electric Power Research Institute (EPRI), the Tennessee Valley Authority (TVA), and other federal, state and private research institutes and universities in the United States and Canada.

A uniform set of collectors is planned for use at each collection site. Samples of precipitation and dry particulate matter will be collected at each site according to a specified schedule and shipped in specially provided containers to a central laboratory or regional analytical laboratories for analysis. During the establishment phase of network operation, most sample collections will be made on a regular schedule but selected stations will make collections on both a precipitation "event" (rain, snow, hail or dust storm) and a timed-sampled basis. Precautions will be taken to preclude changes in, or contamination of the samples during collection and transport prior to analysis. Analyses will be performed as soon as possible after shipment.

During the initial phase, analyses will be made for as many as possible of the following elements, ions, or other properties of each sample: SO_4, NO_3, NH_4, PO_4, Cl, F, Br, K, Na, Ca, pH, total and free acidity or alkalinity, and electrical conductivity. Later, as analytical capacity and interest develop, certain additional elements and substances may be added including total P, Zn, Cu, Mo, Pb, B, Ni, Cd, V, Mn and organic acids. In addition, analyses could be made for other air-borne materials including various pesticides, abestiform fibers, and other substances. Automated systems of analysis will be used wherever possible to keep analytical costs as low as is consistent with reliability and relevancy in the results.

Development of the Network is envisioned as an evolving process extending over several years. It will begin with a small number (20-25) of collection stations in a limited geographical area and a modest list (10-15) of chemical parameters. Later, as more knowledge is acquired, the Network will grow in geographical area and completeness in terms of chemical parameters. Over time, the Network data will also increase in value for testing of hypotheses about source-sink relationships for major pollutants, mechanisms of atmospheric deposition for particular elements, atmospheric transport and transformation processes, and relevancy to known biological and ecological effects of atmospheric deposition.

To ensure that the network data are of such high quality that they enjoy maximum credibility for a wide variety of fundamental-research and mission-oriented purposes, an Analytical Standards Committee of impartial experts will be appointed. This Committee will critically and firmly oversee the operation of the network and its analytical laboratory(ies) so as to control and certify the quality of the data.

All data obtained by the proposed network will be made available to all potential users as soon as possible after analyses are completed. Any portion or all of the data will be provided upon request for any purpose of analysis or interpretation by personnel of any cooperating agency, public or private, which may wish to use the data. A highly flexible computerized system will be used to provide the data in maximally useful form.

SUMMARY

The major purpose of this paper is to describe certain aspects of the changing chemistry of precipitation and its effects on forest vegetation and surface waters. The data presented emphasize the need for a network of precipitation measuring stations in the United States and Canada to provide information about changes in the deposition of beneficial nutrient elements as well as potentially injurious substances. Such information is needed to permit prudent management of anthropogenic emissions of atmospheric trace constituents and the aquatic and terrestrial ecosystems in which these emissions and their transformation products are deposited.

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Plant-Pollutant Interactions and the Oak Ridge Approach to Air-Pollutant Impact Analysis[1]

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Abstract.--The processes by which pollutants move from the atmosphere to sites of action within plant cells are influenced by a wide variety of physical, chemical and biological factors. Of major importance among these are the physical and chemical form of the pollutants, the kinetics of the pollutant exposure regime, the solubility of pollutants in cell systems, and their biological reactivity. The impact of a given dose on plant response is mediated by the above factors as well as many plant-related variables. Present needs in air pollution research relative to interactions of these factors are discussed with special emphasis on chronic impacts of potential regional scale significance.

INTRODUCTION

Although the phytotoxic effects of air pollutants have been recognized for over 100 years, scientists are still challenged by many unanswered questions in efforts to accurately assess air pollutant impacts on vegetation. The problem stems partly from the innate complexity of chemical, physical and biological processes through which plants and pollutants interact, and partly from the fact that the questions themselves are changing.

The purpose of this discussion is first to highlight some of the major factors involved in air pollutant impact analysis, and second, to describe some of the studies under way at ORNL which we hope will reduce some of the uncertainties involved in those analyses.

These studies include investigations of the transport, fate, and biological effects of both gaseous pollutants and particulate contaminants. Major emphasis will be placed on studies involving gaseous pollutants with individual projects ranging in scope from detailed physiological studies designed to consider short-term changes in growth-related processes to regional scale analyses designed to examine impacts on large temporal and spatial scales. The rationale behind these investigations will serve to stress what we see as primary challenges of both the present and the future in the area of plant-pollutant interactions.

The study of air pollution impacts on vegetation is, in simplest terms, a study of dose and response. The major challenge of air pollution researchers in both the field and in the laboratory is determining what doses and responses are significant in terms of developing a capacity to predict ultimate impacts in real world situations. How do we characterize dose so that it reflects the potential for phytotoxic effects, and what processes do we measure to determine whether an adverse response has occurred?

Consideration of Pollutant Dose

Averaging Interval

As a product of two continuous variables, concentration and time, dose may be described

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in an infinite number of ways. Normally, gaseous pollutant exposures are characterized as concentration averages over some time interval. The time interval chosen, however, is quite critical in determining the consistency with which the average will describe phytotoxic potential. Figure 1, for example, indicates four obviously different ways in which an exposure equal to the current secondary ambient air quality standard for SO_2 (e.g., 3h avg = 0.50 ppm) may occur. This same total dose may have widely varying peak concentrations, short-term averages, and pollutant-free intervals. The selection of a biologically meaningful averaging interval is related to the biochemical and physiological processes involved with pollutant uptake and activity in living cells. Since plant leaf tissues appear to have a limited potential for oxidizing the very toxic sulfite ion (formed initially when SO_2 is dissolved in cell liquids) to the less toxic sulfate form, the short-term averages may be quite critical in determining ultimate damage at the cellular level. Based on extensive field studies in Germany, Stratmann (1963) has suggested that averaging intervals of 15 minutes may be more appropriate for describing phytotoxic potential of SO_2. More definitive studies are needed to ascertain this, however.

Exposure Frequency

Another potentially important consideration of dose, which is not reflected by short-term averages, is the frequency of exposure of vegetation throughout the growing season. While physiological processes such as photosynthesis may show only temporary suppression in response to single exposures in the laboratory, the response of photosynthetic processes after repeated exposures, such as may occur in the field, has not been assessed. Present EPA air quality standards reflect the current emphasis on single episodes which may produce visible injury and ignore the frequency of lower levels which may produce chronic stress at cellular or biochemical levels.

Pollutant Combinations

An additional consideration in dose description is the occurrence of multiple exposures involving more than one pollutant. Pollutants normally occur in the field in combination, and there is increasing evidence to indicate that pollutants may interact in modifying plant responses (see review by Reinert et al. 1975). Effects produced by pollutant combinations have

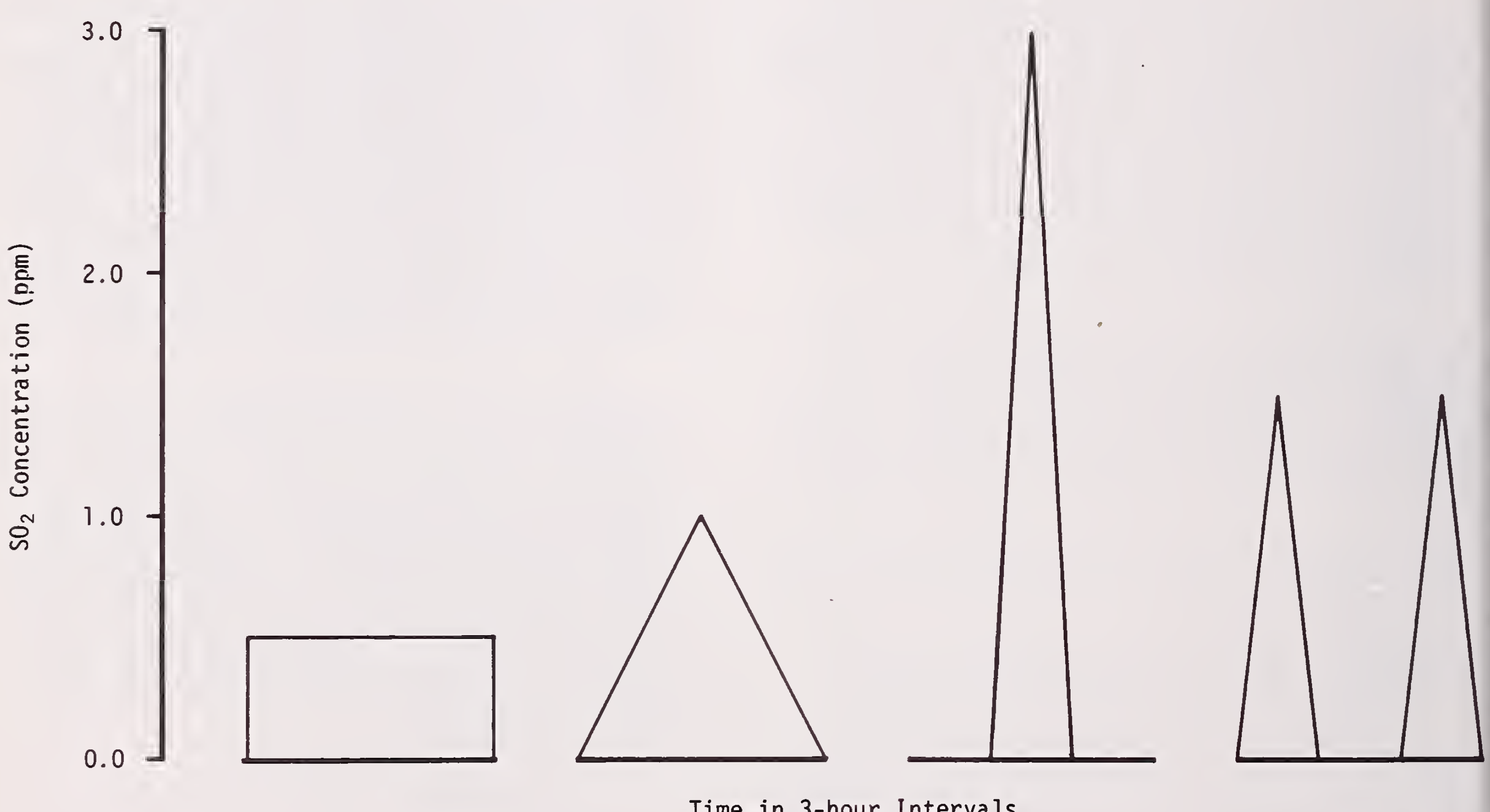

FIG. 1. SOME POSSIBLE OCCURRENCES OF A 3 HOUR AVERAGE SO_2 CONCENTRATION EQUAL TO 0.5 PPM.

been shown to be antagonistic, additive, or synergistic depending on the process studied and the relative concentrations of pollutants involved. Most of the data have been accumulated in laboratory experiments involving mixtures of SO_2 and O_3 or SO_2 and NO_2. The occurrence of additive effects on plant growth following chronic exposure to very low levels of SO_2 and O_3 (0.05 ppm/ 0.05 ppm) in some studies (Tingey et al. 1971) indicates that pollutant combinations may well be significant in regional scale impacts on terrestrial plant ecosystems. Such evidence also indicates that multiple exposures should be considered an important component in studies designed to consider pollutant dose.

Additional Considerations

While the external concentrations of pollutants to which plants are exposed are critical in determining the likelihood of a response, it is the quantity and form of pollutant which reaches the metabolically active tissues which determines whether a response will occur. As primary absorbing organs, leaves and roots are particularly susceptible tissues. Important factors determining the quantity of a pollutant reaching these tissues are its solubility in cellular fluids, its inherent biochemical reactivity, and the ease with which it is detoxified or eliminated by plant cells. Additional variables influencing the impact of a pollution episode are the environmental conditions before and after exposures and the phenological stage of the plant at the time it is exposed.

Plant Response to Pollutants

Responses of plants to air pollutants may be categorized both in terms of the type of effect produced (e.g., foliar injury, reduced growth or reproduction, increased morbidity, mortality) and the time scale (acute or chronic) over which these effects occur. With increased control of atmospheric emissions we may expect a shift in importance of these responses toward more subtle changes produced over longer time periods. While localized acute effects still occur around some point sources, the advent of tall stacks and emission controls can be expected to reduce these impacts to minor proportions. Potentially more significant are chronic impacts resulting from regional scale enhancement of pollutant burdens.

Types of Chronic Impacts

Due to differences in modes of occurrence, sites of action, and the facility with which biological systems can metabolize individual pollutants, chronic air pollution effects on vegetation may occur in a variety of ways. Initial definition of the characteristics of the pollutant exposure regime is extremely critical to a thorough understanding of the types of effects that may be produced and the temporal scale on which they may occur. Exposure regimes that produce chronic low-level effects may result from repeated episodic exposures to concentrations just below the level required for visible damage, or from long-term accumulation of toxic materials absorbed at low levels from the edaphic or atmospheric environment. Three major types of responses may result from chronic air pollutant insults to individual organisms; reduced growth, altered reproduction, and increased morbidity (Smith 1974). Collectively, these responses form the basis for concern for larger scale alterations of ecosystem structure and stability. The responses, however, are evidences of more fundamental impacts of pollutants on basic physiological processes upon which living systems depend. Characterization of the physiological basis of these effects improves our understanding of the mechanisms of toxicity and thereby facilitates the evaluation of probable risk to environmental systems from projected levels in the atmospheric or edaphic environment.

Experimental Approaches to Plant-Level Effects

Probable mechanisms and pollutants potentially responsible for reduced growth, reduced reproduction and increased morbidity, are shown in Table 1. Pollutants included with each process are those for which specific effects have been documented and those whose biochemical symptomology strongly implicate them as probable causal agents. The wide range of processes listed in this table accentuates another problem facing plant researchers, the choice of a suitable plant response. Much of our concern for chronic low-level effects of air pollutants stems from indications that growth of plants may be affected at levels of pollutants below those associated with visible injury to foliage. The diverse responses listed in Table 1 indicate that ultimate growth effects may result from a general deterioration of cellular processes. Many of these process level effects, however, may be secondary reactions resulting from changes in membrane permeability accompanied by a loss of essential levels of subcellular organization and control. Nevertheless, the variety of physiological processes affected indicates that there is a very high potential for very subtle physiological changes which may be accentuated in the presence of stresses which occur naturally in the field.

Table 1.--Types of chronic low-level effects and probable mechanisms involved

Type of effect	Probable mechanisms	Pollutants involved[1]
Reduced growth	Decreased photosynthesis	SO_2, O_3, NO_x, HF, PAN, Pb
	Increased respiration	HF, SO_2
	Biochemical changes	
	Enzyme inhibition	SO_2, O_3, PAN, HF, As
	Electron (energy) transport	HF, O_3, PAN
	Effects on photopigments	SO_2, HF, O_3, PAN, NO_x
	Stomatal function	SO_2, O_3
	Membrane permeability	O_3, PAN, SO_2, HF, metals
	Premature senescence of leaves	SO_2, O_3, PAN, NO_2
	Physical changes	
	UV reflectivity	Acid rain
	Heat exchange	Acid rain
	Gas exchange	Acid rain
	Changes in symbiosis	O_3, acid rain
	Effects on nutrient flux	SO_2, acid rain
Reduced reproduction	Reduced carbohydrate availability for reproductive structures	SO_2, O_3, HF, PAN, Pb, NO_2
	Effects on reproductive processes	
	Flower or fruit production	Smog, HF, SO_2
	Pollen germination or tube elongation	SO_2, O_3, HF
	Mutagensis	SO_2
	Effects on pollinating insects	HF
Increased morbidity	Inadequate carbohydrate supply to support autotrophic respiration and resist disease. Reduced growth and loss of ability to compete with other vegetation	SO_2, O_3, HF, PAN, NO_2, heavy metals

[1]Includes pollutants for which specific effects have been documented and those whose biochemical symptomology strongly implicate them as probable causal agents.

While detailed biochemical and cytological studies have provided researchers with a considerable body of data (Zeigler 1973; Mudd and Kozlowski 1975) to indicate the potential damages of air pollution stress, changes in growth, reproduction, or morbidity represent the final integration of underlying physiological processes. Quantification of plant-level effects on these processes under field conditions, however, is quite difficult because of the difficulties of separating pollution effects from those of the many other variables which also affect these processes.

A particularly promising technique for examining plant responses to pollutants in the field involves the use of charcoal-filtered chambers to exclude pollutants from the air supplied to test plots (Heagle et al. 1973; Mandl et al. 1973). Comparisons of growth and yields of crop plants grown under these conditions with those at adjoining plots grown in ambient air have been used to assess pollutant impacts of soybeans both in the East where plants were exposed to regionally elevated levels of gaseous pollutants (Howell, R. H., personal communication), and near point source emissions of SO_2 from a fossil fuel power plant in Alabama (McLaughlin 1974). In both experiments, yields were reduced by approximately 30% in ambient air compared to those attained in charcoal-purified air. While this approach appears promising as an assessment tool, there are still some questions about possible physiological changes which may enhance the sensitivity of plants grown in chambers of this type. These are being investigated by researchers presently and answers should be forthcoming.

Ecosystem Level Responses

Even more difficult to quantify than organismic responses are those which may occur at the ecosystem level. These may be classified as changes in overall productivity, system diversity, or system stability. Evidence for these types of changes has come mainly from studies around point sources where distance-related gradients have been examined (see review by Miller and McBride 1975). The changes generally follow a well-recognized stress response pattern (Woodwell 1971) where tolerant species known as "generalists" replace the more advanced (i.e., complex) seral stages of forest succession.

Evidence of changes of this type over large areas currently impacted by chronic air pollution are relatively rare in the literature, primarily because such changes are chronic in nature and necessitate long-term studies of a type rarely conducted. There is already evidence, however, that certain species such as lichens (Hawksworth and Rose 1974) and white pine (Ellertsen et al. 1970) may be eliminated or reduced in response to regional increases of pollutants, primarily sulfur oxides. Although changes in structure or diversity of whole ecosystems due to low-level air pollutant effects can be expected to initially be gradual and very subtle in nature, Treshow (1968) has stressed that ecosystems are delicately balanced systems and their structure may depend on a relatively few matrix species. The process of environmental deterioration may be slow, but once natural balances are sufficiently disrupted, subsequent alterations may be more precipitous due to more rapid irreversible changes. The incidence of disease for example may be greatly accelerated as plants are gradually weakened to the point where disease resistance is lowered.

Changes in ecosystem stability may also result from direct effects of pollutants on soil and soil microorganisms (Treshow 1968). The effects of acid rain on both soil and soil microorganisms represent a very real regional-scale stress on these systems. Low-level inputs of relatively immobile trace metals may also, over a long period of time, further stress microbial or soil systems to produce subtle regional-scale impacts of the type already being recognized in close proximity to smelting operations. While many of these low-level effects can currently only be deduced from extrapolation of our present practical experience with somewhat higher levels, our concerns should be real. They point to a drastic need for more research in the area of chronic low-level impacts.

New Challenges

While we are still coping with some of the old questions, additional questions are being posed with the development of new technologies. Having learned from past examples of "afterthought technology," decision-makers very justifiably would like biological research and engineering technology to be interfaced as soon as is practical while the technologies are being developed. An example is the developing coal conversion technology designed to produce clean burning, low-sulfur synthetic fuel oils and natural gas (Richmond et al. 1976). The processes currently being developed involve hydrogenation of coal under high pressure and temperature. The reducing atmosphere of these processes may release a variety of inorganic and organic effluents to the atmosphere which have not been associated with coal combustion (at least in comparable quantities), and consequently have been studied very little or not at all. These effluents include reduced sulfur and nitrogen compounds, and a wide variety of aliphatic and aromatic hydrocarbons. Very little is currently known about the persistence, toxicity and ultimate fate of many of these compounds in aquatic or terrestrial ecosystems. There is a clear need for research to provide a basis for making decisions regarding coal conversion technology which serve both economic and environmental objectives.

The preceding discussion has stressed some of the more important considerations which air pollution researchers must address in quantifying potentially significant interactions between plants and pollutants. The following overview of selected research efforts in progress at Oak Ridge National Laboratory illustrates some approaches being taken in our air pollution research programs.

Ongoing Air Pollution Research Programs at Oak Ridge National Laboratory (ORNL)

A. Ecological Effects of Coal Combustion: Response of Vegetation to SO_2, O_3, and Acid Precipitation

This project is examining plant physiological responses to three pollutants which are either associated with, derived from, or interact with atmospheric emission from coal combustion. It encompasses a series of laboratory and greenhouse studies emphasizing the determination of critical aspects of dose and plant response to SO_2, O_3, and acid precipitation. Results of these studies will be used to determine the type and level of responses to be expected as a result of exposure of plants to subacute levels of these pollutants. With

pollutant dose, primary emphasis is being placed on achieving exposure levels and kinetics which will closely approximate those occurring under field conditions. Exposure kinetics are being varied with SO_2 to consider the effects of peak and short-term average concentrations, repeated exposures, and exposure history. Ozone will eventually be added concurrently to determine the significance of interactions in modifying responses noted with SO_2 alone. With acid rain experiments, initial emphasis is being placed on determining the range of responses produced by rather high (pH 3.2) levels of acidity in simulated rainfall. Ultimate experimental designs will vary acidity levels both between and within rainfall events and exposure frequency to determine critical dosage characteristics. The possible role of acid precipitation in sensitizing plants to SO_2 and O_3 will also be examined. Principal plant responses being measured include photosynthesis, respiration, water use efficiency, and growth. Initial studies are being conducted with kidney beans with eventual experimentation to include seedlings of yellow poplar, white oak, shortleaf pine, and loblolly pine.

B. Effects of Coal Conversion Effluents on Vegetation

The development of coal conversion technologies has raised questions regarding potential environmental problems resulting from a variety of potentially toxic organic and inorganic byproducts. Our program in coal conversion effects at ORNL has developed in response to these questions and represents an effort to provide an "environmental feedback loop" to development of the technology by identifying at an early stage principal toxic components of atmospheric effluents from the process. The approach being taken involves near-term laboratory exposures of plants to gases representative of major classes of compounds with expected phytotoxicity. Eventual testing will include exposures involving gaseous mixtures collected from an experimental coal conversion facility being developed at the Laboratory and at planned pilot and demonstration plants being developed through ERDA/ industrial cooperative agreements. Gaseous compounds which are being utilized include hydrogen sulfide, carbonyl sulfide, carbon disulfide, phenol, carbon monoxide, methane, ethylene, benzene, and xylene. Experiments are designed to determine exposure levels required for both acute and chronic toxicity of individual compounds and mixtures. Data derived from these studies will be utilized to determine both the types and levels of control required to minimize effects of coal conversion effluents on terrestrial vegetation.

C. Interactions of Air-Borne Contaminants with Forest Systems

Air pollutants enter the biogeochemical cycles of forested landscapes by the processes of wetfall and dryfall, or in litterfall following deposition on and/or uptake by foliage. ORNL is currently involved in a number of programs aimed at quantifying mechanisms of input, subsequent biogeochemical fate, and biological effects of air-borne contaminants on forest systems. Studies of the type described below are being used in a number of ways including validation of air transport models, identification of net fluxes and sites and rates of accumulation of contaminants in forest systems, and quantification of mechanisms of biological impact on ecosystem processes.

(1) <u>Wet and dry deposition of particulate contaminants on a forested watershed</u>. These studies involve investigation of the mechanisms regulating inputs of contaminants by wetfall and dryfall processes including the role of canopy scavenging in element cycles. Elemental inputs are being monitored by a series of 6 wetfall, throughfall, and settled particulate collectors distributed throughout the 97.5 ha Walker Branch Watershed research site at Oak Ridge. In addition, periodic sampling of foliage from selected species of trees at several locations has been carried out during the past growing season to determine chemical speciation and relative amounts of various contaminants retained on foliar surfaces. Major emphasis is on deposition of Cd, Pb, Zn, Mn, and SO_4 to leaf surfaces. Preliminary analyses indicate that processes of deposition and impaction have conventionally been greatly underestimated and that these processes augment dryfall deposition to levels much above those expected from ground level dryfall measurements.

(2) <u>Biogeochemical fate of pollutants in forest systems</u>. Watershed studies of nutrient fluxes through forest systems have played a key role in ORNL's involvement in ecosystem analysis research during the past 5 years (Curlin 1970; Henderson and Harris 1975). Sampling and analytical techniques employed in quantification of nutrient fluxes have recently been utilized to describe biogeochemical cycling of contaminants through the forested Walker Branch Watershed (Andren et al. 1975; Van Hook et al. 1976). These studies have been aimed at determining the distribution of contaminants in vegetative and soil profiles and the rates and sites of accumulation of these contaminants in components of biogeochemical cycles. While the distribution and cycling of Cd, Pb, and Zn have been determined (Van Hook et al. 1976), the recently derived budget for sulfur (Shriner and Henderson, in preparation) is of particular interest in view of present concern over regional-scale

loading of terrestrial systems with sulfur derived from fossil fuel combustion. Present analyses indicate an annual input of 18.8 kg ha^{-1} yr^{-1} with an annual accumulation of 7.5 kg ha^{-1} yr^{-1} for Walker Branch. Of this total, approximately 59% is accumulated in the mineral soil with the remainder in the biomass pools of the vegetation and litter components. These studies are continuing in efforts to follow and project long-term changes in forest ecosystem response from regional sulfur loading.

(3) Monitoring biological response of forests to heavy metal contamination. Experience in systems analysis based on Walker Branch studies was recently applied to investigations of the effects of a lead smelter on forests of the Crooked Creek Watershed in southeastern Missouri (Watson 1976). These studies were designed to determine the fate of heavy metals (primarily Pb, Zn, Cd, and Cu) deposited on the forested landscape and the effects of these metals on various ecosystem components. The greatest accumulation in biological components occurred in the forest floor litter where inhibition of microbial decomposition occurred. Metals remineralized from the litter layer were leached into the soil where active uptake by plant roots occurred. Ecosystem level effects documented in this study include: (1) accumulation of incompletely decomposed deciduous litter, (2) decreased microbial activity out to 2 km from the stack, and (3) depressed macronutrient pools out to 0.8 km. Evidence collected to date indicates that a disruption of normal nutrient cycling processes has occurred. The areal extent of these effects may increase with continued deposition of heavy metals and can be expected to eventually result in decreased productivity of the impacted forests.

D. Modeling Pollutant Transport

An air transport model (Mills and Reeves 1973; Culkowski and Patterson 1976) which was jointly developed by researchers at ORNL and the NOAA Atmospheric Turbulence and Diffusion Laboratory at Oak Ridge, currently provides a capability for describing the distribution of atmospheric pollutants around sources of a variety of types. This type of information will be quite important in ultimate efforts to interface dose-response information with levels of pollutants to be expected over vegetated landscapes. The ATM is a Gaussian plume model developed to predict atmospheric concentrations of air pollutants at distances ranging from 0.1 to 50 km from point, area, or line sources. Operation of the model requires basic information on the physical characteristics of the source(s), source strength and diffusion coefficients of effluents of interest, and meterological parameters (principally wind direction and velocity, and temperature lapse rate). In addition to calculating concentration regimes of gaseous pollutants, the ATM has been coupled with the Wisconsin Hydrologic Transport Model (Patterson et al. 1974) to provide estimates of wetfall and dryfall deposition rates of aerosol constituents. An important flexibility of the ATM is the capability of predicting episodic concentrations of pollutants (including maximum groundline concentrations under adverse meterological conditions) over time intervals as short as one hour. Longer distance transport may also be considered by coupling the ATM with the Trajectory Windrose Model of Heffter (1975). The ATM is currently finding applicability in a variety of research areas, including prediction of pollutant inputs to watersheds, estimation of the effects of industrial siting on regional air quality, and prediction of maximum groundline concentrations of airborne effluents from developing technologies. Such information is used in designing experiments to test probable toxicity of expected effluent concentrations.

E. Modeling the Response of Forest Systems to Air Pollution Stress

The patterns of growth and succession observed in developing forest systems may be considered to have resulted from interactions between the inherent potential of individual species to reproduce and grow initially at a site, and biotic and abiotic stresses subsequently experienced at that site. Among the abiotic stresses which have been speculated to cause long-term changes in forest systems is chronic exposure to air pollutants. A forest stand growth and succession model, FORET, developed at Oak Ridge by Shugart and West (1976) is currently being examined as a tool to project potential alterations in stand growth and composition as a result of stresses imposed by chronic levels of air pollutants. The model was designed to simulate changes in growth and successional patterns of eastern forests. Validation of the model was performed by examining the response of forests to the removal of American chestnut by the chestnut blight. The model functions similarly to the forest growth model developed by Botkin et al. (1972). Growth of individual trees is simulated on 1/12 hectare sample plots for any specified species combination and simulation time desired. The model will be used to project probable impacts of pollutants on forest growth and succession by examining the differential effects of pollutants on various tree species. Data derived from past field and laboratory studies with trees are being used to determine relative sensitivity of different species. Tests will be run to determine both levels of effect and requisite time intervals for significantly altering forest growth and development.

Our overview of these projects has served to emphasize that air pollution impact analysis is a multifaceted task requiring an integration of efforts from activities in a variety of fields. Ultimate characterization of impacts on terrestrial ecosystems will require the combined efforts of effluent characterization, transport modeling, and characterization of biogeochemical fates, as well as the more commonly attempted dose-response studies conducted by plant scientists. While coupling these processes in an integrated assessment represents a significant challenge to air pollution researchers, the tremendous economic costs of both pollution control and the consequences of increased pollutant stress on terrestrial ecosystems demand that it be vigorously addressed.

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Research Advances in Terrestrial Effects of Environmental Pollutants[1]

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Abstract.--Research on the terrestrial effects of environmental pollution is presently evolving from the traditional static, single pollutant acute dose/response studies on selected individual plant and animal species to dynamic ecological investigations of multiple pollutants, chronic effects on complex terrestrial ecosystems, components and processes. Examples are discussed in the context of need for continued development and relevance to whole systems problems.

INTRODUCTION

Terrestrial ecology research supporting Federal environmental pollution control programs historically has been associated with air pollution legislation since 1955. Until 1973 the productivity of "welfare" effects research called for in the Clean Air Act of 1970 was related principally to the acute effects of individual "criteria" pollutants on specific crops, trees and other vegetation. This work, conducted cooperatively with the USDA, Agricultural Research Service and Forest Service, provided the scientific support for the establishment of national secondary air quality standards and other pollution control strategies. Continuing work with "criteria" and other gaseous pollutants is being directed toward more representative simulation of ambient pollution exposures which are characterized by stochastically (randomly) varying concentrations over time and pollutant mixes as they may occur in the real world. The effects of these exposures on selected crops and tree species are being measured in terms of reduced yield and/or marketability of the product to provide damage function information for economic loss analysis.

Recent recognition of the broader ecological implications of environmental pollution has generated new initiatives in plant/soil process studies, including nutrient cycling, soil litter decomposition and nitrogen fixation. This work indicates a need for further in-depth research on the long term, chronic impact of single and mixed pollutants, including trace elements and heavy metals as well as end products of gaseous emission transformations (e.g., sulfates and acid precipitation). The entire matter of long term chronic effects on whole terrestrial ecosystem dynamics remains to be unraveled before any assurance of the adequacy of pollution control strategies can be assumed.

Other new EPA initiatives in terrestrial ecology research include a coal-fired power plant field study in eastern Montana to support the Federal energy program and a pesticide substitute-chemical project designed to develop methodologies for scfeening new candidate pesticides. In both these programs the scope of investigation ranges from single species effects to whole system components, including ecological niches and natural food chain dynamics.

Although existing legislation and present resources in terrestrial ecology effects research are still based on support for only single species dose/response studies, the following topics relating to basic physiological processes and broadened whole ecosystems problems illustrate the current evolution in air pollution effects research.

AMBIENT EXPOSURE SIMULATIONS

A valid and serious criticism of air pol-

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lution research on plants has been the poor relationship between experimental exposures (single pollutant, continuous, generally high concentrations in control chambers) and ambient exposures experienced by plants in the "real world." This shortcoming resulted in the rescinding of the long term (one year average) secondary air quality standard for sulfur dioxide in 1973.

Since that time, experimental methodologies have become more sophisticated. Controlled pollution doses have been made more realistic through application of stochastic modeling to air pollution surveillance data from key locations in the national monitoring network. Crop plants and tree species used in experimental studies now "see" randomly varying pollutant levels, concentration ranges and pollutant mixes which simulate real conditions at varying distances from point and non-point sources. Results from these studies provide new insight into the season-long growth effects and yield reductions associated with single and multiple pollutant exposures.

Another innovative approach is being field tested in eastern Montana. The Zonal Air Pollution System (ZAPS) provides a way to dispense controllable levels of gaseous pollutants over an area of up to one acre. This is accomplished, with minimal disturbance of the natural ground cover, through a system of pipes with appropriately spaced orifices suspended within two feet of ground level. Preliminary analysis of data for the first season of operation indicates good controllability of pollutant concentrations at ground level. Further testing and refinements may permit broader use of ZAPS for controlled exposure studies.

STRESS ETHYLENE

Ethylene is one of many volatile reactive hydrocarbons emitted as a byproduct of green plant metabolism. Preliminary investigations show that the ethylene production rate is a sensitive measure of plant physiological stress. Although the precise mechanism is not yet understood, concentrations of gaseous pollutants (ozone and SO_2) well below existing national standards cause measurable increases in ethylene emissions by selected plant species.

This phenomenon is being investigated to determine 1) whether elevated ethylene production levels can be correlated reliably with reduced crop and forest growth and 2) what contribution this and other reactive hydrocarbon gaseous emissions from vegetative cover may make to ambient background levels of photochemical oxidant precursors in rural and remote areas. Results of this work will provide a new perspective for developing future regional air pollution control strategies.

NITROGEN FIXATION

Existing secondary air quality standards for photochemical oxidants and sulfur dioxide are related to the visible effects of these pollutants on plant foliage. Recent findings indicate that the process of nitrogen fixation in the rhizosphere of growing legumes and forest trees may be substantially impaired by pollution levels well below the present standards. Based on the importance of nitrogen fixation in the biosphere and the apparent sensitivity of this process to pollution stress, current plant and soil investigations over a wide range of environmental pollutants have incorporated nodulation and nitrogen measurements to reflect effects on nitrogen fixation.

These measurements are included in studies of such diverse problems as gaseous air pollutants, acid precipitation, trace elements, pesticides and solid waste. Nitrogen fixation may indeed be considered a "sentinel" process which can serve as a primary indicator of pollution-caused ecosystem stress.

SOIL LITTER DECOMPOSITION AND NUTRIENT CYCLING

The rate of natural conversion of forest litter to humus and recyclable nutrients is considered an indicator of forest productivity. Reductions in the soil litter decomposition process caused by environmental pollution stress may, therefore, impact the long term growth of selected tree species. The extent and significance of these relationships are being investigated in ongoing field and laboratory research which is addressing the problems of photochemical oxidants, sulfur dioxide, acid precipitation, and trace element/heavy metal pollution.

TOXIC SUBSTANCE UPTAKE AND TRANSLOCATION

Root, leaf and seed crop plants grown in treated soil of varying chemical and physical characteristics can be used to test uptake and bioaccumulation of introduced toxic substances, including trace elements and heavy metals commonly found in phosphate fertilizers, industrial waste and pesticide residues. Tests recently conducted at the EPA's Corvallis Environmental Research Laboratory showed uptake of cadmium, contained in phosphate fertilizers, by radish, lettuce and peas. Percentage of Cd in fertilizer recovered was 5.3, 9.0 and 2.0, respectively. The highest concentration recovered was over 6 μg/g dry weight in lettuce when

fertilized at the rate of 100 µg P/g soil with concentrated super phosphate containing 174 µg Cd/g fertilizer (.087 µg Cd/g soil).

CONCLUSIONS

Considerable development is underway in approach, techniques and scope of investigations relating to terrestrial effects of environmental pollutants. Cooperation and involvement among a broader segment of ecologically based skills and disciplines will further enhance the advancement of knowledge in whole systems problems.

Natural Atmospheric Cleansing Processes[1]

W. G. N. Slinn[2]/

Abstract.--Residence times for atmospheric trace constituents are defined and the separate contributions from wet and dry removal and from chemical transformations are displayed. Three methods are outlined for estimating wet removal's contribution to the residence time; dry transfer through the atmosphere and deposition to various surfaces are discussed. A number of worked examples demonstrate state-of-the-art estimates for atmospheric residence times of particles and gases and where future research is needed.

INTRODUCTION

When considering natural atmospheric cleansing processes it is convenient to distinguish, separately, wet and dry removal processes. Wet removal or precipitation scavenging proceeds via the incorporation of air pollutants into precipitation (rain, snow, hail, graupel, etc.) and the subsequent deposition of the pollutants at the earth's surface. As was seen in the paper by Cowling (this volume) this process can significantly influence the chemistry of the precipitation; in this paper, however, the emphasis will be on the role precipitation scavenging plays in cleansing the atmosphere. Dry removal or dry deposition proceeds without the aid of precipitation and, as was seen in the paper by McLaughlin and Shriner (this volume) plant-pollutant interactions can be a major factor in the efficiency of dry removal processes. Thus, for example, pollutant-plant interactions dictate relatively rapid dry removal of HTO or $^{14}CO_2$ and, in contrast, essentially zero removal of ^{85}Kr. Besides these pollutant-plant interactions, though, it is necessary to consider dry deposition of particles and gases to a variety of other surface types. Some general features of these topics will be presented here. Details about a third important "removal process", viz. chemical transformations in the atmosphere, will generally be avoided both because of my limited knowledge and because these transformations usually must be treated on an individual-case basis.

It was requested that the general thrust of this presentation be aimed at defining problems and discussing possible solutions in the general area of air pollution removal processes. In my opinion, the main problem is to determine atmosphere residence times for pollutants. This problem is a subset of the general problem to determine health and environmental consequences of pollution releases. It is admittedly true that in many cases these consequences can be correlated directly with pollutant air concentrations or, in some cases, directly with local pollution releases. However, the importance of atmospheric cleansing processes becomes apparent when attempts are made to relate local air concentrations to distant sources; e.g., to relate sulfate concentrations in New York to sources in Pennsylvania, Ohio, or even in New Mexico. In cases such as these it is necessary to evaluate pollutant removal between sources and sinks. To summarize the rest of this presentation, my best "guesstimate" is that: for aerosol particles released in the troposphere, there is a distribution of residence times with mean value (approximately equal to the variance!) of about one week; for gases, the residence times can vary from a few hours or less for very reactive gases (whose "removal" is dictated by chemical transformation) to about 10^7 years for helium. The main problems, then, are to increase the accuracy of these estimates and to explain their variability. In this presentation, the emphasis will be on how these residence times are estimated, what is the source of the variability, why there remain inaccuracies in the estimates, and where future studies could help reduce some of the uncertainties.

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RESIDENCE TIMES

As will be seen, there are a number of different ways to estimate atmospheric residence times. Incidentally, other names with which similar "residence times" are identified are "lifetimes", "turnover times", or sometimes, "e-fold times". One method to estimate pollutant lifetimes is similar to the usual estimator for human lifetimes: add the measured lifetimes of n humans and divide by n. However, it is essentially impossible to determine the lifetime of individual gas molecules or aerosol particles and it is difficult and/or expensive to mount substantial tracer experiments to obtain similar information. As an alternative, the average lifetime of a total of N people can also be determined if the population has reached a steady state with B, births = D, deaths per unit time interval. Then the average lifetime

$$T = N/B = N/D. \qquad (1a)$$

Similarly, if a steady state has been reached between production P and removal R of an air pollutant, leading to a total quantity Q in the atmosphere, then the residence time is

$$T = Q/P = Q/R \qquad (1b)$$

As an example of the use of (1), consider sulfur compounds in the atmosphere. Their average mixing ratio is about 1 ppbm and therefore, since the mass of the troposphere is 4×10^{21}g, Q=4 Tg. Natural and anthropogenic sources sum to give P = 200 Tg yr^{-1} within a factor of about 2. Consequently, the lifetime of sulfur compounds in the troposphere, Q/P, is about one week. This estimate could already have important practical value: it would suggest that, indeed, SO_2 releases from, for example, the Four-Corners power plants could result in increases in sulfur concentrations on the east coast of the U.S. However, this estimate for the lifetime of sulfur compounds is not accurate, at least to within a factor of 2 and possibly to within as much as an order of magnitude.

To improve the accuracy of the residence time as given by (1), it is necessary to obtain more accurate and/or representative information about Q and either P or R. For pollutants with relatively short residence times and/or point sources, there can be great variability in the air concentrations and therefore in estimates for Q. For example, SO_2 concentrations in the U.S. meet and sometimes exceed the EPA primary standard of 365 $\mu g\, m^{-3}$ (24-hr average) and yet, sometimes within a matter of hours, the SO_2 concentrations can fall to near background levels of a few $\mu g\, m^{-3}$. This variability, to a greater or lesser extent, is a characteristic of all atmospheric trace constituents and reflects variations in air trajectories, removal processes, and source strengths. Qualitatively, it is expected that the longer the pollutant's residence time the smaller would be the concentration variations (e.g., as measured by the coefficient of dispersion, f, which is the standard deviation divided by the mean) since the longer the residence time, the greater the opportunity for atmospheric turbulence to suppress fluctuations. Indeed, Junge (1974) recently proposed an ingenious semi-quantitative method to estimate residence times of pollutants of recent concern (e.g., the low molecular weight halogenated hydrocarbons) using the empirical result T = 0.14 yr/f. However, even if Q is known reasonably accurately, inaccuracies in R and P can limit the accuracy of estimates for T based on (1). For example, Junge (1963) used fairly reliable estimates for the total precipitable water vapor in the troposphere in 10° latitude belts and divided these Q's by annual average rainfall in each belt to obtain appropriate T values (typically about one week, with some latitude dependence). Nevertheless, as pointed out by Junge, these estimates can not be considered too reliable since steady state conditions rarely prevail and mixing between latitude belts was ignored. Further, though, perhaps all removal processes were not included since apparently much water vapor is removed to the oceans in the dynamic process of evaporation and condensation; if account is taken of this "dry deposition" of water vapor, the estimated residence times might necessarily be reduced to about 2/3 the values given by Junge. Alternatively, T can be estimated from Q/P but uncertainties can enter in estimates for P, especially if a substantial fraction of the "pollution" is actually from natural sources. For example, in the case of aerosol particles, certainly a major (but unknown) fraction of the global-averaged amount is of natural origin. In the case of sulfur compounds, it can be somewhat amusing to conclude from various estimates made during the past fifteen years, that the sulfur from natural H_2S sources has progressively fallen from 170 to 160 to 30 to 20×10^6 tons yr^{-1}! In summary, then, many uncertainties enter into the use of (1) and consequently it is compelling to seek alternative methods for estimating atmospheric residence times; in particular, to develop quantitative understanding of the removal processes themselves.

WET REMOVAL

There are a number of ways to estimate wet removal's contribution to a pollutant's atmospheric residence time. Perhaps the simplest conceptually follows from assuming that the average fraction $\bar{\varepsilon}$ of pollution entering a

precipitating storm is scavenged by the storm. Further, let the average time between storm encounters be $\overline{\nu}^{-1}$. Then it is simple to deduce the estimate for the pollutant's residence time if only wet removal processes are acting:

$$\tau_w = (\overline{\varepsilon}\,\overline{\nu})^{-1} \qquad (2)$$

If it is further assumed that precipitating events form a stochastic Poisson process then familiar results can be used to deduce the probability of any number of scavenging events in a given time period. As an example of the use of (2), if for particles $\overline{\varepsilon} = .25$ and if $\overline{\nu} = (2.5\text{d})^{-1}$ then $\tau_w \simeq 10$ d. At present, however, the practical value of (2) is severely restricted because of almost total lack of information about $\overline{\varepsilon}$ and $\overline{\nu}$. Notice that the average storm frequency $\overline{\nu}$ is actually in a Langragian sense, moving with an air "parcel". Conceivably, $\overline{\nu}$ could be estimated from global circulation models but, to the author's knowledge, this task has not been undertaken. Also, if the average fraction of pollutant removed per storm $\overline{\varepsilon}$ is written as

$$\overline{\varepsilon} = \overline{\varepsilon}_i\,\overline{\varepsilon}_{cw}$$

where $\overline{\varepsilon}_i$ is the average fraction of pollution entering the cloud water and $\overline{\varepsilon}_{cw}$ is the average efficiency with which storms precipitate cloud water, then the unsolved meteorological problem of estimating cloud water removal efficiencies becomes apparent. Presumably this can vary from essentially zero to perhaps as much as 90%. Thus, in summary, although τ_w as given by (2) is simple in principle, lack of knowledge severly restricts its practical value.

A method for estimating τ_w which has considerably more practical value relies on a widening data base for washout ratios. The washout ratio r is the ratio of the pollutant's concentration in precipitation to its concentration in surface level air: $r = (\kappa/\chi)_0$. From a recent tabulation of measured ratios (Slinn et al, 1977) it is seen that for trace metal aerosol particles typically $0.1 \lesssim r \lesssim 0.5\text{x}10^6$ (dimensionless). Similar values have also been obtained for the reactive gases NH_3, NO_2, and SO_2 where, in these cases, the ratios are of the reaction product mass concentration in rain to the precursor-gas mass concentration in surface level air. A semiquantitative analysis by Junge (1963) demonstrates the reasonableness of aerosol particle and reactive gas washout ratios near 10^6. Thus, if the average fraction $\overline{\varepsilon}_i$ of the pollutant entering a storm is incorporated into cloud water, then the concentration of the captured pollutant is $\overline{\varepsilon}_i\langle\chi\rangle$ units per volume or $\overline{\varepsilon}_i\langle\chi\rangle/\langle L\rangle$ units per mass of cloud water, where χ is the pollutant's air concentration, L is the condensed water content of the cloud and the braces, ⟨ ⟩, represent an average over the storm. If this concentration $\overline{\varepsilon}_i\langle\chi\rangle/\langle L\rangle$ also appears in the precipitation from the storm (which would be true for gravitational coagulation of equally polluted drops and for no evaporation or dilution enroute to the earth's surface) then the volumetric concentration in surface level precipitation, χ_0, would be $\overline{\varepsilon}_i\rho_w\langle\chi\rangle/\langle L\rangle$. With $\langle\chi\rangle/\chi_0 \simeq 1$, $\rho_w = 1$ g cm^{-3}, $\langle L\rangle \approx 10^{-6}$ g cm^{-3} then this gives $r = (\kappa/\chi)_0 \simeq \overline{\varepsilon}_i 10^6$. Recently, Junge (1975a) reviewed estimates for $\overline{\varepsilon}_i$ which include nucleation and Brownian attachment of particles to cloud particles and from this review it can be concluded that values in the range $0.1 \lesssim \overline{\varepsilon}_i \lesssim 1$ are quite to be expected. For gases which form simple solutions in cloud water, then an adequate approximation is to set $\kappa_0 = H^{-1}\chi_0 = \alpha\chi_0$ where H is (one form of) Henry's law constant and $\alpha = H^{-1}$ is the solubility coefficient; therefore, in this case, $r = \alpha$. Using tables of solubility coefficients (e.g., Slinn et al, 1977) it is found that the washout of such gases is generally ignorable. Given the washout ratio, the wet flux is $W = rp_0\chi_0$ where p_0 is the surface level precipitation rate, or the wet deposition velocity, W/χ_0, is $v_w = rp_0$. For example, with $r = 0.3\text{x}10^6$ and $p_0 = 100$ cm yr^{-1}, then the annual-average wet deposition velocity would be $v_w \simeq 1$ cm s^{-1}. Consequently, a simple mass balance in a volume of the atmosphere of scale height $h_w = \int\chi dz/\chi_0$ from which pollution is removed by wet processes, gives

$$\tau_w = h_w/v_w = h_w/(rp_0). \qquad (3)$$

For example, if $h_w = 10$ km and $v_w \simeq 1$ cm s^{-1} then $\tau_w \simeq 10$ days. To improve the accuracy of (3), it would be useful to increase the data base of washout ratios and it is essential to obtain some firm information about h_w.

A third way to estimate wet removal's contribution to a pollutant's atmospheric residence time depends on detailed considerations of collision processes and transfer rates to arrive at formulations for rain, snow, etc. scavenging rates, Ψ. However, space limitations recommend against describing details here (see, e.g., Slinn 1976a,b). In outline, for the case of rain scavenging of particles, it is first necessary to consider various processes (e.g., inertial impaction, interception, Brownian diffusion, and various phoretic processes) which are responsible for the collision between an individual particle and a raindrop. Then integrations are performed over all drop sizes and, if a particle mass-average scavenging rate is desired, over all particle sizes. When a number of approximations are introduced the result is

$$\tau_w = \Psi_r^{-1} = [cpE(\overline{a}, R_m)/R_m]^{-1} \qquad (4)$$

and a similar result for snow scavenging. As an example of the use of (4), for c = 0.5, p = 100 cm yr^{-1}, an average collection efficiency $E \simeq 10^{-2}$ and volume-mean drop radius, R_m = 0.25 mm, then $\tau_w \simeq 10$ days. To improve the accuracy of τ_w as given by (4), and similarly for snow, it is most essential to obtain more accurate estimates for the long term average collection efficiencies; they are uncertain by about an order of magnitude!

DRY REMOVAL

In contrast to wet removal, dry deposition is a surface phenomenon; nevertheless, it is important to consider dry transport through the atmosphere since in many cases this downward transport can be the rate limiting stage of the overall dry removal process. A result that illustrates this point is the detection of Sahara dust at Carribbean sampling sites; in this case, vertical transport down through a capping inversion from desert warmed air aloft inhibits the dust's deposition to the ocean. To quantify this concept it is useful to introduce the familiar resistance model which, similar to diffusion K-theory, can be described as "not useful in principle, only in practice" (credited to Corrsin by Gifford, 1968). To develop a resistance model for the atmosphere it is convenient to define first an overall, downward transfer velocity k_a with which the dry flux becomes $D = k_a(\chi_A - \chi_E)$. Here the subscripts A and E on the air concentration χ represent some convenient layer aloft and at the earth's surface, respectively. In this form, the flux is proportional to a "driving" concentration "potential difference"; the proportionality constant k_a then appears like an electrical conductance. Next, if the atmosphere is considered to be divided into a series of layers A, B, C, and D (which might identify, for example, aloft, boundary, constant flux or canopy and deposition layers) and if the flux is the same through all layers, then conductances for each layer can be defined via $D = k_A(\chi_A-\chi_B) = k_B(\chi_B-\chi_C) = k_C(\chi_C-\chi_D) = k_D(\chi_D-\chi_E)$. Alternatively, $D = k_a(\chi_A-\chi_E) \equiv k_a[(\chi_A-\chi_B) + (\chi_B-\chi_C) + (\chi_C-\chi_D) + (\chi_D-\chi_E)]$ and upon substituting into this last expression $(\chi_A-\chi_B) = D/k_A$, etc., we obtain the desired result

$$k_a^{-1} \equiv r_a = r_A+r_B+r_C+r_D \equiv \Sigma(k_I)^{-1}. \quad (5)$$

In this form it is seen that the overall resistance to transfer through the atmosphere $r_a \equiv k_a^{-1}$ is equal to the sum of the resistances in the individual layers, $r_I = k_I^{-1}$. It is of course true that different meteorological conditions can cause substantially different resistances in different layers, e.g., for Sahara dust transport across the Atlantic. However, on a long-term-average basis, it appears that $r_A+r_B+r_C$ typically sum to about 1 s cm^{-1} (i.e., the average transfer velocity to the layer immediately adjacent to the surface is about 1 cm s^{-1}). In contrast, though, the transfer resistance for many pollutants is substantially larger in the deposition layer or within the receiving surface, itself. Consequently it is necessary to consider these surface and near surface resistances in more detail.

For global scale pollutants, the most important surface receptors are the oceans. In general, knowledge about pollutant dry deposition to oceans and lakes is severely restricted by a lack of data (for a review, see Slinn et al, 1977). Probably most is known for gases (Liss and Slater, 1974). In this case, it is convenient to identify, separately, transfer through the atmosphere or gas phase, $D = k_g(\chi_b-\chi_i)$ and transfer in the liquid phase, $D = k_l(C_i-C_b)$. Here the subscripts g, b, i and l represent gas phase, bulk, interface and liquid phase where the bulk concentration are measured at convenient heights (depths) in the atmosphere (ocean). At the interface, at least for gases which form simple solutions, Henry's law prevails: $\chi_i = HC_i$. Finally, if an overall transfer velocity is defined via $D = k_0(\chi_b-HC_b)$ where HC_b is the air concentration which would be in equilibrium with the existing bulk concentration of the gas C_b in the liquid, then algebra as in the previous paragraph leads to

$$\frac{1}{k_0} = \frac{1}{k_g} + \frac{H}{\alpha^* k_l} \quad (6)$$

where $\alpha^*>1$, an effective solubility coefficient, has been introduced so that this formalism can also be applied to the case of reactive gases; for example, for SO_2, $\alpha^* \simeq 10^3$ (Liss and Slater, 1974). In (6) the overall resistance k_0^{-1} is seen to be the sum of an atmospheric resistance $r_g = k_g^{-1}$ plus a resistance in the liquid phase $r_l = [H/(\alpha^* k_l)]^{-1}$. In Liss and Slater's survey, they conclude that the following values are representative, long-term-averages for the oceanic case: $k_g \simeq 0.8$ cm s^{-1}, $k_l \simeq 20$ cm hr^{-1}. Similar values can be expected for lakes. With this information and data and theory for H and α^* these authors conclude that for gases of low solubility (H near unity) and unreactive in seawater (α^* near unity) then $r_l \gg r_g$ (e.g., N_2, O_2, CO_2, CH_4, N_2O, noble gases) and therefore the overall transfer is controlled by liquid phase transfer. In contrast, for gases with high solubility ($H \ll 1$) and/or rapid acqueous phase chemistry ($\alpha^* \gg 1$) then $r_g \gg r_l$ (e.g., H_2O, SO_2, NO_2, NH_3, NCl, HF). Certain pesticides and PCB's (see later) are borderline cases between these two extremes. In the case of particles, liquid phase resistance can be ignored and the net dry flux can be parameterized in terms of deposition and resuspension velocities (Slinn, 1976c): $D = v_d\chi_b - v_rC_b \equiv v_d(\chi_b-\chi_*)$ where χ_* is the particle concentration

in air which would be in equilibrium with the existing bulk particle concentration C_b in the ocean. The particle dry deposition velocity v_d (or k_g) appears to depend primarily on transfer across the atmosphere's viscous sublayer. Available water/wind tunnel data (Möller and Shuman, 1970; Sehmel and Sutter, 1974) suggests that at low to moderate wind speeds the dominant contributors to particle dry deposition to the ocean are simply Brownian diffusion and gravitational settling: $v_d \simeq v_g + 0.8$ cm $s^{-1}/Sc^{2/3}$ where v_g is the gravitational settling velocity and $Sc = \nu/D$ is the Schmidt number in which ν is the kinematic viscosity of air ($\nu \simeq .15$ cm^2 s^{-1}) and D is the particle diffusivity in air. If this data can be extrapolated to the oceanic case then it suggests that dry deposition of particles to the ocean is generally ignorable compared to wet deposition. However, this data and no existing theories properly account for capture of particles by spray, particle impaction on realistic waves, phoretic effects, or particle growth by water vapor condensation (Slinn et al, 1977.) Consequently it is clear that much further research is required in this subject area before accurate assessments can be made.

Similar analyses are appropriate for dry deposition of particles and gases to surfaces on land. From the recent review by Chamberlain (1975) it is seen that most resistance to the transfer of reactive gases (SO_2, I_2, O_3) to vegetation or moist soil occurs in the atmosphere. This leads to the familiar transfer velocity of about 1 cm s^{-1} (or $u_*^2/\bar{u}$ or a few percent of $\bar{u}$ where u_* is the friction velocity and $\bar{u}$ is the mean wind speed at a convenient reference height, usually 1 m above the canopy). However, even for reactive gases, the surface resistance is expected to become increasingly important when stomata are closed, humidity is low or, for example, for dry sandy soil. Nevertheless, assuming a long-term-average transfer velocity of about 1 cm s^{-1} for transfer of reactive gases across the lower atmospheric layers to typical surfaces in the northeastern U.S. is probably one of the more accurate assumptions made. For less reactive or less soluble gases (e.g., CO_2, NO, PAN, CO) the data obtained by Hill and Chamberlain (1976) suggests that the dry transfer is controlled within the surface receptor (Slinn, 1976b). The best available procedure for residence time estimates for such gases is probably to use the available data, even though the vegetation used in the laboratory experiments may not be representative for the area of interest. A substantial amount of information is available about dry deposition of particles to smooth surfaces (for a review, see Slinn, 1976d) but most of this information can not correctly be applied to typical environmental problems. In contrast, very little is known about particle dry deposition to rough surfaces and vegetative canopies. Preliminary data (e.g., Sehmel and Hodgson, 1976) and theory (e.g., Slinn, 1976b) suggest, however, that the filtration effect of canopies is, in many cases, sufficiently great so that dry deposition of particles, regardless of size, can be assumed to be controlled by transfer through the upper layers of the atmosphere. If correct, this will result in the reappearance of the ubiquitous dry deposition velocity of about 1 cm s^{-1} (or $u_*^2/\bar{u}$). Further research is definitely required here; indeed, in view of suggestions of soon-to-be-promulgated sulfate regulations in the U.S., it can be said that research results are required urgently.

To develop estimates for dry removal's contribution to a pollutant's residence time it is necessary to obtain suitable parameterizations not only for the transfer velocities but also for the pollutant's vertical distribution in the atmosphere. This can be seen from a simple box (or control volume) model and leads to

$$\tau_d = h_d/k_0 \qquad (7)$$

where k_0 is the overall transfer (or dry deposition) velocity and $h_d = \int \chi dz/\chi_b$ is a dry deposition scale height. Notice that although h_d has the same form as the similar wet scale height h_w introduced in (3), nevertheless these two heights are not expected to be the same since, for example, the integral defining h_w is to be evaluated only during periods of precipitation. As an example of the use of (7), if h_d = 5 km and k_0 = 0.5 cm s^{-1} then $\tau_d \simeq 10d$. In contrast, many authors are apparently inclined to use substantially different values in (7) and to conclude that dry removal is substantially more efficient; e.g., with $h_d \simeq 1$ km which is a typical, annual-average mixed depth for the northeastern U.S. (Holzworth, 1972) and $k_0 \simeq$ 1 cm s^{-1} then the numerical value of (7) is about 1 day. However, such estimates fail to appreciate even the common nighttime inversion which essentially shuts off transfer to the surface of pollution mixed more deeply during the previous day. It is inadequate simply to average the nighttime and daytime mixed heights and it should also be appreciated that with low nighttime inversion conditions or large scale subsidence then wind speeds are frequently lower, further reducing the dry deposition velocity. Note also that pollutants trapped above an inversion are usually transported farther by the higher wind speeds. As a first-order alternative in the case of relatively weak large scale atmospheric motions, perhaps it would be more appropriate to assume for summertime conditions that every night, dry removal completely cleans the lowest, say, 300 m and that during the day, dry removal from the, say, 2 km mixed height is negligible.

This simple model yields $\tau_d \simeq 1$ wk. Certainly, however, further research is required that properly accounts for the meteorological factors influencing dry removal.

CONCLUDING EXAMPLES

To conclude this presentation it might be of interest to demonstrate estimates of residence times for a number of atmospheric trace constituents, if for no other reason than to emphasize some of the uncertainties. In the general case when wet and dry removal as well as transformations participate in a pollutant's removal, then the residence time is given by

$$\frac{1}{\tau} = \frac{1}{\tau_w} + \frac{1}{\tau_d} + \frac{1}{\tau_t} \quad . \tag{8}$$

If it is desired to envision an electrical analogue for (8) then the different removal paths appear like resistances in parallel. As briefly mentioned earlier, for some pollutants the smallest resistance is via physical/chemical transformations. For example, τ_t for SO_2 is probably about 1 day although it appears to depend strongly on humidity, insolation, and concentrations of other trace gases such as NH_3. Photochemical transformations probably dominate the "removal" of some of the otherwise-almost-inert, low molecular weight halogenated hydrocarbons of recent environmental concern although the rate limiting stage may be their transport to the stratosphere ($\sim$ years). However, consistent with the rest of this presentation, the emphasis here will be on removal dictated by wet and/or dry deposition.

Early estimates for the residence time of aerosol particles suggested a strong dependence on particle size but more recent results, referenced earlier, suggest that if there is any dependence at all, it would be quite modest. Thus, particles smaller than 0.05 μm radius rapidly coagulate with larger particles, including cloud particles, and with collectors at the earth's surface. Essentially all larger particles can act as cloud droplet nuclei and, even if they do not, preliminary evidence suggests that dry deposition to most environmental surfaces is much more efficient than to smooth surfaces in the laboratory. Still, however, the long-term average residence time of particles is not known at least to within a factor of 2 or 3. Notice that if $\tau_w \simeq \tau_d \simeq 10$d is substituted into (8) then $\tau \simeq 5$ days.

In contrast to the suggested, particle-size-independent residence time for aerosols, it is clear that the residence time for gases is strongly dependent on their chemical reactivity and solubility in water. Gases with large solubility coefficients (e.g., for the pesticides: DDT, $\alpha = 6.2\times10^2$; Aldrin, $\alpha = 1.9\times10^3$; Lindane, $\alpha = 5.0\times10^4$; Dieldrin, $\alpha = 1.3\times10^5$; data from Junge, 1975b) are quite efficiently removed by rain or by dry deposition to lakes, oceans, and other surfaces with substantial water. For example, since for these gases the washout ratio $r = \alpha$, then from (3) τ_w for Dieldrin is about 10 days and estimates for the other listed pesticides can be scaled proportionately with the inverses of their solubility coefficients. From (6) it is seen that these large solubility coefficients dictate that dry transfer to lakes and oceans is rate limited by transfer through the atmosphere. However, it is suggested (Münnich, 1971; Slinn et al, 1977) that it is inappropriate to use a transfer velocity to the oceans of about 0.8 cm s^{-1} because of the reduced Brownian diffusivity of these large molecules. For example, if the appropriate reduction factor is $Sc^{-2/3}$ as for particles, then for DDT $k_g \simeq 0.1$ cm s^{-1} and then from (6) and (7), $\tau_d \simeq 1$ mo. For some of the PCB's with $10^\circ \leq \alpha \equiv \bar{H}^{-1} \leq 10^2$ (Junge, 1975b) and for gases such as $^{14}CO_2$ ($\alpha \simeq 1$) then their transfer is liquid phase controlled. For $\alpha = 1$ and $k_l \simeq 20$ cm hr^{-1} then from (6) and (7), $\tau_d \simeq 3$ yrs which, although quite long, is substantially shorter than the corresponding values of τ_w. For other gases such as CO_2 ($\tau \sim 10$ yrs) and O_2 ($\tau \sim 10^3 - 10^4$ yrs) it should be mentioned that these values might more appropriately be described as atmospheric turnover times to emphasize that biological or geological processes actually control their ultimate removal from the atmosphere (Junge, 1972).

Finally, it may be of interest to address a practical problem of considerable recent interest in the U.S. The problem is to identify and possibly control sources which contribute to the potential health hazard from annual average sulfate concentrations in many parts of the northeast in excess of 10 μg m^{-3}. Some suggestions derived from this review are, first, that probably most SO_2 released from tall stacks at fossil fuel plants is not dry deposited with a value near 1 cm s^{-1} and $\tau_d \simeq 1$ d; instead, because of rate limiting transfer aloft especially during nights, τ_d would be several to perhaps 10 days. Meanwhile, however, most SO_2 is probably oxidized to $SO_4^=$ and these sulfate particles would be expected to have an average residence time of about 5 days. Of course, large variations about the average value are to be expected. This suggests that all upwind sources within about 1000 miles of a given site contribute to its atmospheric sulfate burden. However, resuspension of previously deposited and of natural sulfate particles should not be underestimated, especially because the chemical form of the sulfate particles sampled at air monitoring stations is rarely determined and because the price tag for SO_2 controls is so high. Thus, for example, it should not go unnoticed that high concentrations of sulfate particles sampled in Texas and Utah are probably resuspended, innocuous, neutral salts (Junge, 1963; Slinn, 1976e). The most important point to be derived

from this survey, however, is that our present understanding of atmospheric removal processes is still quite primitive.

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Dry Removal of Air Pollutants by Vegetation Canopies[1]

J. G. Droppo[2]

This study describes studies being conducted to quantify dry removal rates of air pollutants by natural surfaces. Processes involved are discussed in a resistance model framework. Values from the literature and results of current field tests relating to rates of dry removal are summarized for selected gases and particles, and the experimental accuracy of particulate sulfur deposition values is discussed.

INTRODUCTION

Concern about the fate and effects of atmospheric pollutants has intensified interest in natural removal processes. One of these processes is dry deposition of gases and particles on vegetative canopies, the subject of studies currently underway at Battelle's Pacific Northwest Laboratories. Rates of removal by vegetative canopies and other surfaces are being measured in field studies to determine pollutant budgets on large scales and to assess local impacts from single sources. These data will be used as input to mathematical prediction models of dry deposition processes.

Dry deposition is the direct transfer of a material from the atmosphere to vegetation or any other material which comprises the earth's surface by processes other than those involving liquid water droplets. Dry deposition reduces ambient air pollutant concentrations and determines the potential for an increase in the pollutant concentration on or within the receptor material. Processes affecting dry deposition of a specific pollutant include gravitational settling, transport by atmospheric turbulence, impaction, concurrent surface fluxes, and chemical reactions. Quantification of these processes is necessary to evaluate potential pollutant impacts, both in the air and on the receptors. Battelle is developing a comprehensive model which evaluates dry deposition of pollutants on various surfaces under varying conditions. This paper describes the model, reviews dry deposition data for a number of pollutants on various canopies and surfaces, and gives results of current studies.

MODELING OF DRY DEPOSITION PROCESSES

Past efforts to model dry deposition of smaller particles and gases have been limited by a lack of data defining the relative importance of the various operative processes. The following model description, which is based on synthesis of a number of references (Bennett et al., 1973; Droppo, 1974; Garland, 1974b; Hicks, 1974; Wagonner and Reifsnyder, 1968; Hill, 1971; Rasmussen et al., 1974; Select Research Group in Air Pollution Meteorology, 1974; Slinn, 1974), provides a conceptual framework for organizing these processes for subsequent study. This model is similar to the resistance models proposed for water vapor fluxes from canopies. Dry deposition may be considered as a concurrent flux to the surfaces and in certain cases to plant stomata.

The dry deposition of a substance may be a function of many processes, or one process may dominate all the others. A typical list of interrelated factors would include:

Atmospheric factors:	Wind speed, turbulence, temperature structure, moisture, concentrations of pollutant being studied

1/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, MO, Nov 16-18, 1976.

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	and other pollutants, solar radiation and long wave radiation.
Receptor factors:	Surface roughness, moisture, physical and chemical nature, physiological state, membranes, internal and surface pollutant concentrations, and status of stomata.
Pollutant factors:	Chemical and physical properties, solubility densities, size, shape, settling velocity.

Dry deposition involves flux by many different transport mechanisms. These include gravitational settling, atmospheric eddy transport, and molecular transport in the air near the surfaces and from the surfaces into the receptor. These mechanisms may be grouped into regimes: 1) the atmospheric regime, 2) the surface air layer regime, and 3) the surface-into-the-receptor regime. Various processes dominate the transport in each regime.

The atmospheric regime refers to the air layer over the surfaces. In this regime pollutant transport is primarily by eddy motions of air. The surface air layer regime refers to the thin layer immediately over the receptor, where molecular transport is important. The surface-into-the-receptor regime refers to the rate at which pollutants are transported into the receptor. In this regime molecular transport, physiological and chemical processes may variously dominate the flux.

The chemical change of one pollutant species to another is a sink that may be a parallel process in any of the regimes. When considering the constant flux layer chemical reactions within the atmospheric regime are not normally rapid enough to be significant. Reactions at the surface (such as destruction of ozone) and within the surface (such as physiological uptake of SO_2) (deCormis, 1968) can be limiting in some situations. The model does not consider the potential for saturation of various sinks. For example, a plant's resistance to a pollutant may be a function of the concentrations already within the plant. Consideration of such factors by the model would mean that time must be included as a variable in the analysis.

Each regime is assigned a resistance (r) which defines the extent to which that regime limits the deposition rate. For a given situation:

$$\frac{1}{r_T} = \frac{1}{r_a + r_\ell + r_i} + \frac{1}{r_g} \qquad (1)$$

where the subscripts T, a, ℓ, i and g refer to total, atmospheric, surface air layer, internal (surface into receptor), and gravitational resistances. Once total resistance is defined, boundary condition inputs into diffusion models are possible.

Resistance Terms in the Model

Each of the resistance terms on the right of Equation 1 can be considered as a separate input for the dry deposition process in this formulation of the model. These terms are discussed below.

Atmospheric Resistance

The transport processes for a given pollutant in the atmospheric regime can be described in terms of the transfer processes for other materials or properties. For example, the atmospheric resistance for the material might be assumed to be equal to that of momentum (τ),

$$r_a = r_\tau = \frac{u(z)}{u_*2} \ . \ . \ . \qquad (2)$$

where $u(z)$ is the wind speed at height z and u_* is the friction velocity. This is the reciprocal of a relationship developed by Chamberlain and Chadwick (1953) for a "deposition velocity".

Surface Resistance

The dependence of deposition on near-surface mechanisms comprises the surface resistance term r_ℓ. Owen and Thompson (1963) defined this resistance, which arises from molecular interaction in the layer just over the surface, in terms of a nondimensional Stanton number (B^{-1}).

Equation 2 assumes that the total resistance for momentum is atmospheric. The mechanisms of transport at the surface for momentum and mass differ. Momentum is transferred by pressure forces on the receptor, while mass must be carried to the surface by gravity, impaction or molecular transport mechanisms. The latter processes result in the surface resistance.

Internal Resistance

For plant tissue, resistance is a more complicated function of the plant properties and processes. Factors such as membrane pressures and pollutant concentrations may limit transport. The opening and closing of stomata

is important for gases. Control of stomata openings for certain plants has been shown to depend in a complicated fashion on the ambient air concentrations of CO_2, H_2O and SO_2. Hence, resistance in plants appears to be the most difficult persistence to assess, since the actual properties of the surface and receptor must be defined.

Rates of Reaction Resistances

The limiting processes may be different for gases, such as ozone, which are highly reactive. Destruction of ozone occurs at the surfaces and perhaps also in areas shaded from sunlight by the surfaces. The gravitational resistance term (r_g) gives a lower limit for the rate of any deposition. The resistance is the inverse of the appropriate settling velocity V_g,

$$r_g = \frac{1}{V_s} \tag{3}$$

Effective Surface Resistance

An effective surface resistance, r_s, is used to include processes other than atmospheric and gravitational. That is,

$$\frac{1}{r_T} = \frac{1}{r_a + r_s} + \frac{1}{r_g} \ . \ . \ . \tag{4}$$

In practice the effective surface resistance is the additional resistance a pollutant encounters over the atmospheric eddy delivery resistance. The potential rate of transport in the atmospheric eddy transport regime is assumed to be the same for all gases and small particles, a function of atmospheric turbulence alone.

Deposition Velocity

The simplest relationship for dry deposition of either gases or particles is based on an assumption relating the ambient air concentration (χ) and the rate of deposition (G). The rate of deposition is assumed to be directly proportional to the ambient air concentration at a defined height over the surface (z). The constant of proportionality incorporates the units of length per time and is referred to as a "deposition velocity" (V_d) (Chamberlain and Chadwick, 1953). The equation is:

$$G = v_d/\chi_z \tag{5}$$

with the height traditionally assumed to be 1 meter. The deposition velocity has been a framework for much of the research in dry deposition and will be used for summarizing these previous efforts. The deposition velocity through all regimes is the inverse of the total resistance:

$$V_d = \frac{1}{r_T} \tag{6}$$

Gases

Table 1 is a summary of dry deposition velocity data for various gases on different surfaces. Iodine, SO_2, O_3, NO_2 and HF all have reasonably high deposition velocity values. The limited data on NO indicate a much lower value. The high and low relative deposition rates of NO_2 and NO are supported by the intermediate value for NO_x.

The effect of vegetative canopies on deposition is not clearly defined. For example, increases in surface roughness and area are expected to lead to high deposition rates. Although this is generally true for SO_2, the rougher surface (pine forest) has a lower deposition velocity than other canopies and surfaces. Other factors discussed earlier may be limiting the deposition.

The effect of atmospheric delivery is obvious in the data that include groupings by atmospheric stability. These studies of the deposition of SO_2 and other gases demonstrate that various regimes may be limiting under differing conditions and that a range of deposition velocities can result.

Several studies have considered the penetration of materials into canopies by dry deposition. Markee (1971) considered the dry deposition of iodine as a function of leaf surface area for low canopies. He found that deposition increased with increasing leaf area. The absorption of gaseous air pollutants by alfalfa canopies and resultant profiles were studied in an environmental growth chamber (Hill, 1971). Hydrogen fluoride, SO_2 and NO_2 profiles suggested efficient removal by both the upper and intermediate surface vegetation. Table 2, which is derived from Hill's data, shows this efficiency of transfer of momentum and gases as a function of height. These data have been normalized to the top height to allow comparison of profile shapes. Assuming the transport mechanisms are the same for all properties in the air, the profiles may be interpreted as reflecting fluxes. These profiles indicate that momentum deposition is more efficient than deposition of the pollutants. Use of momentum deposition velocities will cause overestimation of the flux and the location of the deposition. Although there is significant deposition of the gases (except

Table 1. Summary of Deposition Velocities for Various Gases

Substance	Deposition Velocity (cm/sec)	Type of Surface/ Number of Experiments ( )	Methodology and Reference
Iodine[a]	Range: 1.1 - 3.7 Mean: 2.1	Grass (7)	Field experiments (Chamberlain, 1953 and 1966)
Iodine	Range: 0.3 - 1.3 Mean: 0.75	Clover leaves (4)	
Iodine	Range: 0.6 - 2.0 Mean: 1.3	Paper leaves (4)	
Iodine	Range: 0.3 - 0.9 Mean: 0.62	Filter paper (5)	
Iodine	Range: 0.09 - 2.43 Mean: 0.87	Grass (19)	Field experiments (Bunch, 1966 and 1968)
Iodine	Range: 0.6 - 0.7 Mean: 6.5	Carbon (12)	(Hawley et al., 1966; Markee, 1971; Zimbrick et al., 1969)
SO_2	2.8	Alfalfa canopy in chambers	Windspeed: 1.8 to 2.2 m/s (Hill, 1971)
SO_2	Range: 1.0 - 2.06 Mean: 1.3	Grass (14)	Surface flux determination for SO_2 (Garland et al., 1974a)
$^{35}SO_2$	Range: 0.5 - 2.6 Mean: 1.3	Grass (3)	Radioactivity labeled SO_2 release used as tracer in field experiments (Owers and Powell, 1974)[b]
$^{35}SO_2$	0.5	Water (1)	Radioactivity labeled SO_2 release used as tracer in field experiments (Owers and Powell, 1974)
SO_2	Range: 0.27 - 1.5 Mean: 0.76	Grass (5)	(Shepherd, 1974)
SO_2	1.3	Grass (1)	Surface flux determination for SO_2 (Droppo et al., 1976)
SO_2	1.8	Short grass	Surface flux (radioactive tracer) (Garland, 1974b)[b]
SO_2	(0.84) 1.3	Medium grass	
SO_2	0.91	Bare calcareous soil	
SO_2	2.2	Fresh water (pH = 8)	
SO_2	<0.50	Forest pine	
SO_2	2.4 2.6 0.5	Lapse Neutral Stable	Over grass (Whelpdale and Shaw, 1974)
	1.6 0.52 0.05	Lapse Neutral Stable	Snow
	4.0 2.2 0.16	Lapse Neutral Stable	Water
NO	0	All surfaces	Not a field result (Robinson and Robbins, 1968, 1970)
NO	0.1	Alfalfa canopy	In special chambers (Hill, 1971)
NO_x	0.5	Alfalfa and oats	Derived from data in Tingey (1968) and Rasmussen et al. (1974)
NO_2	2.0	Alfalfa canopy	Special chamber (Hill, 1971)

Table 1. Summary of Deposition Velocities for Various Gases (cont.)

HF	1.6	Alfalfa	Fumigation with constant concentrations (Israel, 1974)
	3.1	Field crops	Fumigation with constant concentrations
O_3	Range: 0.7 - 1.7 Mean: 1.13	Several	Review of research by several authors (Galbally, 1971; Galbally, 1968a,b; Aldaz, 1969; Regener, 1969; Kelly, 1968)
O_3	0.6 - 1.8	Soil, peat, grass	Wind tunnel experiments (Garland, 1974)
O_3	1.4 - 6.3	Several	Decay rate experiment in box (Garland, 1974)
O_3	1.7	Alfalfa canopy	Special chambers (Hill, 1971)

(a) There is some question about how long iodine remains a gas before attaching to particles.
(b) Estimates of surface resistance are also given in this paper.

NO), the deposition clearly occurs deeper into the canopy than does the momentum transfer, as indicated by the changes in concentration with height. Table 2, which gives the percentage changes in layers, shows that the SO_2 change is still relatively large in the lowest layer when compared with changes in the other gases.

Particles

Dry deposition of particles depends on the delivery rate in the atmosphere and on surface interactions. (Larger particles that deposit by gravitational forces are excluded from this consideration.) Transport in the atmosphere is a function of the atmospheric turbulence. At the surfaces the principle processes are impaction and molecular diffusion. Electrical forces may also be important, depending on the mobility and charges of the particles and the electrical field. In addition, concurrent mass and heat fluxes may influence the dry deposition rate when molecular processes are important.

The wide range of field data values for dry deposition of various particles is summarized in Table 3. Included are results from the literature as well as results of current experiments at Battelle. The wide range in the values may have two origins. First, large variations are expected from situation to situation as the processes discussed above become variously limiting. Secondly, variations can be partially the result of experimental uncertainties, which are generally relatively large in dry removal rate experiments.

Table 2. Normalized Wind and Pollutant Profiles (Based on Data in Hill, 1971)

Height (cm)	% Momentum from 60 cm to Height	% SO_2	% O_2	% HK	% NO_2	% NO
60	100	100	100	100	100	100
50	91	92	94	94	96	98
40 (Canopy)	37	69	74	75	90	100
30	13	47	54	59	75	93
20	8	37	42	53	62	92
10	5	22	36	51	57	94
Changes						
60-50	9	8	6	6	4	2
50-40	54	23	20	19	6	-2
40-30	24	22	20	16	15	7
30-20	5	10	12	6	13	1
20-10	3	15	6	2	5	-2

Table 3. Summary of Deposition Velocities for Various Particles

Substance	Deposition Velocity (cm/sec)	Type of Surface/ Number of Experiments	Methodology and Reference
Fission Products	0.07	Gummed Paper	Surface activity measurements particles are formed by an electric core (Megaw and Chadwick, 1956)
^{137}Cs	0.9	Water (5)	Field release test measurements (Slade, 1968)
	0.04	Soil (15)	
	0.2	Grass (21)	
	0.2	Sticky paper (117)	
^{103}Ru	2.3	Water (9)	
	0.4	Soil (16)	
	0.6	Grass (20)	
	0.4	Sticky paper (8)	
^{93}Zr, ^{95}Nb	5.7	Water (6)	
	2.9	Soil (6)	
	1.4	Sticky paper (10)	
^{141}Ca	0.7	Sticky paper	
^{127}Te, ^{129}Te	0.7	Sticky paper (8)	
Pb	0.13	Dilute HCl solution	Plastic pluviometer (Servant, 1974)
Industrial-derived Trace Elements	0.4 to 0.3	Deposition plates	Field data (Cawse and Peirson, 1972)
Soil-derived Trace Elements	0.3 to 1.0	Deposition plates	
Zinc Sulfide (2.5 μm diameter)	0.5	Sagebrush	Stable atmospheric conditions (Simpson, 1961)
Particles of 0.1 μm	0.2 to 9.2	Desert	Islitzer and Dumbauld (1963)
Natural Particulate Material	0.8 to 7.6 (7)	Great Lakes (water)	Whelpdale (1974)
Fallout	0.2 to 3.4	Fallout collectors	Monthly values (Small, 1960)
Fallout	0.51 and .75	Fallout collectors	Annual values
Total Sulfur Aerosol	0.1 to 0.3	Sagebrush (3)	Surface flux technique (Droppo, 1976)

In current dry deposition efforts, there is an attempt to separate these two factors by making an experimental accuracy estimate for each data value obtained. This appears to be a desirable procedure, since initial estimates show that the experimental accuracy of values varies widely from case to case.

Experimental Accuracy for Dry Deposition of Sulfur-Containing Particles

Although our current studies consider removal rates for a number of gaseous and particulate pollutants, the discussion here will be limited to the determination of the dry deposition rates of sulfur-containing particles. Detailed descriptions of our experimental model, equations, assumptions, data aquisition systems, field sites, and results have been documented elsewhere (Droppo and Hales, 1974; Hadlock et al., 1976; Droppo et al., 1976).

With a combined eddy flux-gradient methodology, the accuracy of the deposition velocity computation depends on the accuracy and applicabilities of the eddy diffusivities and the accuracy of the pollutant profiles. Battelle studies indicate that either or both of these experimental accuracies may limit the accuracy of the results (Droppo et al., 1976).

Since the direct determination of pollutant eddy diffusivities is normally not possible, a suitable analogy is assumed in the transport of other quantities for which eddy diffusivity is attainable. The eddy diffusivities that have been studied are known not to be generally identical, although relationships have been derived. The applicability of a given eddy

diffusivity to a pollutant is an open question. The momentum eddy diffusivity was adopted in the current study, although the choice is somewhat arbitrary. Further research is needed to resolve this question.

Figure 1 is a plot of four computed dry deposition velocities for ambient sulfur particles over a sagebrush cover. These are not selected results, but rather four proof tests that were performed to determine how accurately deposition rates could be determined with current surface flux-gradient methodology. The first three cases (but not the fourth) met the criteria for application of the methodology. Conditions of the fourth case varied significantly from steady state, so this case is included for comparison only.

The key to the accuracy of the current methodology for particles was the attainment of sufficient accuracy in the pollutant profiles. The ±1% pollutant profile accuracy assumed in these plots is supported both by relative accuracy estimates in the specially developed X-ray fluorescence analysis (Droppo et al., 1976) and in the "goodness of fit" of the concentration values to a log profile. There are too few data points to make a definitive accuracy estimate. Additional efforts are underway to better define the accuracy of removal rate determinations. Table 4 summarizes these preliminary results in terms of the resistance values defined earlier. R_T is the inverse of the deposition velocity, R_a is the atmospheric resistance (computed as equal to the momentum resistance), and R_s is the effective surface resistance computed as the difference between the total and surface resistances. The last column is the mean wind speed at 17 meters.

As far as we are aware, these preliminary data provide the first values that directly assess sulfur containing particle removal rates in the field within reasonable accuracy. The range and values are encouraging and are positive results in the first stages of this developing methodology.

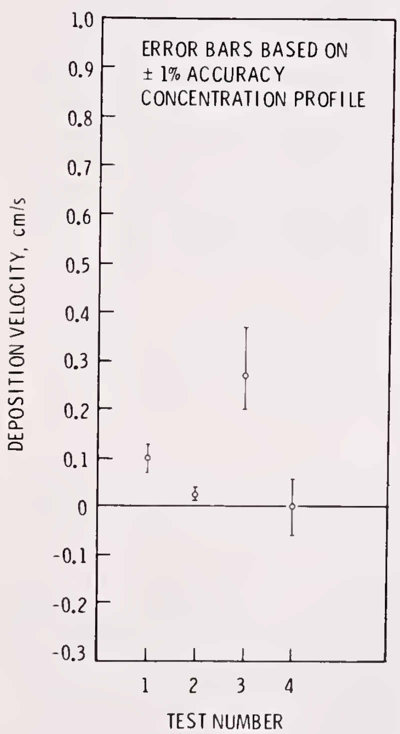

Figure 1. Deposition Velocities for Total Sulfur Particles.

Table 4. Summary of Results for Dry Deposition of Sulfur Aerosols

Test	V_d (cm/s)	R_T (s/cm)	R_a (s/cm)	R_s (s/cm)	$\bar{u}$(17m) (m/s)
1	0.10	10.0	2.3	7.7	1.13
2	0.03	33.3	2.3	31.0	3.50
3	0.27	3.7	0.44	3.3	1.28

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Modeling the Uptake of SO_2 by Vegetation[1]

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Abstract.--Transport of SO_2 is traced from its sources through the atmosphere to the effective sink within the plant. The model is based on the resistance analog to Fick's diffusion equation. At low ambient concentrations environmental parameters are shown to affect SO_2 removal. The model generates information on the uptake of a single leaf. Vegetative parameters include leaf and stomatal factors and LAI (leaf area index). Generalized values of LAI are used to estimate SO_2 uptake on a regional basis. The model is applied to calculate the SO_2 uptake in energy and mineral resource regions of the Western United States where ambient levels of SO_2 will increase as a result of proposed development.

INTRODUCTION

The Northern Great Plains, including Montana, Wyoming, North and South Dakota and Nebraska, contain estimated reserves of 3.3 trillion tons of coal. Much of this coal is low in sulfur and sufficiently near the surface for economical strip mining. The Northern Great Plains Resources Program (NGPRP) (EPA 1974) identified high, medium, and low scenarios for the development of mine-mouth power plants and coal gasification facilities by 1985 and by 2000. In spite of the fact that these facilities will each meet ambient air quality standards as well as the New Source performance standards for sulfur dioxide (SO_2), on a regional basis one must expect some increase in ambient concentration of SO_2.

This increase in pollution comes in air which has been estimated (Fox 1976) to be among the cleanest in the United States. The climate of this region is influenced by a gradation of precipitation from a low of 10 inches annually in eastern Montana and Wyoming to over 22 inches in North Dakota. The native vegetation is a grassland ecosystem, which basically grades with the precipitation pattern from short grass to tall grass prairie. A question of paramount concern is, what impact will the increase in ambient sulfur dioxide have on the natural ecosystem?

This paper represents a multistep procedure to assess the effect of low ambient concentrations on grassland systems. Since consideration of the soil uptake is much beyond the scope of our paper, as is sulfur metabolism in natural grasses, the contribution is limited. Specifically, we develop a numerical model capable of simulating the uptake of sulfur dioxide, and use the model to estimate SO_2 removal by vegetation on a regional basis. As an example, we estimate the incremental uptake in the Northern Great Plains based upon estimates of the ambient concentration associated with the 1985 and 2000 development scenarios.

MODEL

For the purpose of this model an estimated annual average ambient concentration of sulfur dioxide is applied uniformly to the vegetation. At the leaf--atmosphere interface, the flux of gas into the system is governed by a series of resistances. The resistance analog to Fickian diffusion is used to simulate transport through the leaf to an effective sink in the mesophyll. The removal capacity of this sink is a function

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of sulfur dioxide solubility in the water layer surrounding the cells of the mesophyll.

Through the use of the resistance analog, flux through the plant system is estimated by:

$$F_{SO_2} = \frac{C_a - C_i}{R_T} \qquad (1)$$

Where F_{SO_2} = Flux of SO_2 into the plant ($\mu g/m^2$-sec)

C_a = ambient volumetric concentration ($\mu g/m^3$)

C_i = internal volumetric concentration

R_T = total resistance (sec/m)

= $R_b + R_s + R_{ss}$

The resistance is the sum of the boundary, stomatal, and substomatal resistances, since it is assumed that these act sequentially. The boundary resistance (R_b) is given by

$$R_b = \frac{0.4}{D}\sqrt{\frac{L}{\bar{u}}}$$

where

0.4 = empirical coefficient ($cm/sec^{1/2}$)

L = leaf length in crosswind direction (cm)

$\bar{u}$ = mean wind speed (cm/sec)

D = molecular diffusion coefficient for SO_2 in air (cm^2/sec)

= 0.115 cm^2/sec (Chamberlain 1966)

The stomatal resistance (R_s) is given by (Nobel 1974)

$$R_s = (d_s + r_s)/Dna$$

where

d_s = effective stomatal depth (cm)

r_s = stomatal radius (cm)

n = number of stomates per leaf

a = $\frac{\text{area of stomates}}{\text{area of leaf}}$

Radiation is considered to have a second-order effect on stomatal resistance, since the grasses under concern here reach maximum stomatal opening about one hour after sunrise (Meidner and Mansfield 1968):

$$R_{ss} = x/D$$

where

x = mean path length to the cells of the mesophyll from the stomatal pores (cm)

The concentration, C_i, of SO_2 within the plant is an undeterminable quantity. However, since SO_2 is highly soluble in water and since mesophyll tissue is largely water, it is likely that the internal concentration drives SO_2 into solution in the mesophyll water. This approach is similar to that adopted by Murphy et al. (1976) and others. Solubility of SO_2 in water is governed by Henry's Law:

$$C_i = \chi H \qquad (2)$$

where

χ = concentration of SO_2 per unit water volume

H = Henry's Law constant

H is not strictly a constant, but has a rather pronounced variation with temperature. Johnstone and Leppa (1934) published solubility data for low concentrations of SO_2 in water. At temperatures of 0, 10, 18, 25, 35, and 50° C. For use in the model, values of H were required for all temperatures within a range from about 5°C to 40°C. A regression analysis yielded the following equation for H, the Henry's Law constant:

$$H = 0.013697 + 0.000495(T) + 0.000011(T)$$

where T is °C. This equation has an excellent least squares fit (R = .978) and it was used rather than linear extrapolation. It is possible to estimate the incremental increase of concentration due to the calculated flux of SO_2 by plants. This is simply

$$\Delta\chi = F_{SO_2}\frac{A}{V}\Delta t \qquad (3)$$

where

$\Delta\chi$ = increase in concentration of SO_2 in mesophyll water

A = surface area of mesophyll per stoma

V = volume of water in the mesophyll surrounding a typical stoma

Δt = interval of time flux is operating.

The concentration becomes

$$\chi = \chi_0 + \Sigma_i (\Delta\chi)_i \qquad (4)$$

where χ_0 is the initial concentration.

Combining (1)-(4) yields an expression for the flux of SO_2 into a plant as a function of the previous time history so that

$$(F_{SO_2})_{i+1} = \frac{C_a - H(\chi_0 + \Sigma_i(F_{SO_2}\Delta_t)_i\frac{A}{V})}{R_T} \qquad (5)$$

where $(F_{SO_2})_{i+1}$ = flux of SO_2 to the plant at time $t = \Delta t + \Sigma_i \Delta t$

From equation (5) there are two obvious environmental parameters affecting the flux of SO_2 to the plant, wind velocity and air temperature. Velocity affects R_T since boundary layer resistance, R_b, is inversely proportional to the one-half power of velocity. Thus the flux goes as

$$F_{SO_2} \propto \frac{K_1}{K_2 + \frac{1}{u^{1/2}}}$$

for any particular species; that is, it increases as velocity increases. A similar dependence has recently been shown by Murphy (1976). Temperature affects the Henry's Law constant linearly to first order above 5°C. Increasing temperature thus reduces the flux of SO_2 to the plant.

Using equation (5) it is possible to sum over a period of time the total accumulation of SO_2, U_{SO_2}, by a vegetated surface as

$$U_{SO_2} = \Sigma_i (F_{SO_2} \Delta t)_i \text{ A na LAI} \qquad (6)$$

where
U_{SO_2} = total uptake (μ g)
LAI = leaf area index = $\frac{\text{area of leaves}}{\text{surface area}}$

Such uptake will continue so long as there is a sink for SO_2 in the mesophyll, namely until $X \geq X_{sat.}$, where $X_{sat.}$ is the equilibrium saturation of SO_2 in water. In practice, the calculation is performed for 1 sec. time intervals, Δt - 1 sec. until $X \geq X_{sat.}$ at which time the flux is assumed to stop.

The above calculations assume that SO_2 is absorbed into the mesophyll water with no transport of SO_2 across cell boundaries. While the mesophyll water molecules are able to pass freely through cell membranes, SO_2 molecules are not. Translocation of SO_2 and ultimately its metabolism by the plant are far beyond the scope of this paper. We make two critical assumptions in order to estimate uptake of SO_2. First we assume that the plant is able to metabolize all of the SO_2 it receives in the course of a day. Thus X_0 = 0 at the start of each new day. Secondly, the plant is not able to exchange SO_2 outside the mesophyll tissue rapidly enough to dilute the concentration resulting from SO_2 solubility. In calculations described more fully in the next section, the time scale to reach solubility is on the order of 2 hours. Clearly, our uptake estimates will be conservative unless the time scale for the plant to translocate SO_2 is greater than 24 hours. Since it is more likely on the order of 6 hours, one might expect uptakes during the growing season to be greater by a factor of 2 to 3.

Two final assumptions, which relate to the neglect of radiation and water stress in our considerations, need explanation. These assumptions are justified on the basis of climatology of the locations and the physiology of the plants considered. In all but the worst cases of water stress, it seems likely that grass stomates will be open for the minimal amount of time (2 hr.) required to reach saturation. Studies of grasses further indicate that maximum stomatal opening occurs within about one hour after sunrise (Meidner and Mansfield 1968).

RESULTS

The model was applied to calculate sulfur dioxide uptake on a statewide basis for the Northern Great Plains. Ambient SO_2 concentration values were calculated using a simple long-range transport concept (Fox 1976). The model uses statewide estimates of climatology to determine parametric estimates of dry deposition and precipitation removal. Emissions were based upon (a) the "reasonable" development scenario for the year 1985 from the NGPRP (EPA 1974), and (b) the maximum development scenario for the year 2000 (EPA 1974). The entire state area is treated as being under natural vegetation -- range grasses. Vegetative uptake was calculated using the model described in the previous section. Climatological inputs were used for temperature and wind speed, and the ambient concentration was assumed to remain fixed at the calculated level.

A statewide value of leaf area index was determined in order to generate a statewide uptake estimate. Uptake was calculated using equations (1) - (5). Uptake estimates are summarized in Table 1, along with calculated concentrations and dry deposition estimates from the long-range transport (atmospheric) model. Values of the percent of deposited SO_2 that is taken up by vegetation are reasonable when related to the amount of vegetative cover and other uptake estimates for grasses (Spedding 1969). Obviously, estimates for statewide areas vary greatly with leaf area index, since a very large land area is involved.

Accuracy of the area estimates would improve if somewhat smaller, more vegetatively homogeneous surface areas were used. In addition to providing a general guide to a large area uptake, the SO_2 uptake model can also be used in a more refined calculation to provide vegetation removal boundary conditions

TABLE 1.

SULFUR DIOXIDE UPTAKE BY VEGETATION GIVEN ON A STATE BY STATE BASIS

	AMBIENT CONC. $\mu g/m^3$		DRY DEPOSITION kg/state/day		UPTAKE (VEG.) kg/state/day		PERCENT REMOVED BY VEGETATION		VEGETATIVE UPTAKE AS A PERCENT OF DUH
STATE	1985	2000	1985	2000	1985	2000	1985	2000	2000
MONTANA	4.46	6.7	45.7	68.7	1.0	1.5	2.1%	2.2%	14%
WYOMING	3.6	6.0	9.6	14.4	0.6	1.0	6%	6.9%	11%
NEBRASKA	3.3	4.9	7.8	11.5	0.4	0.6	5%	5%	11%
NORTH DAKOTA	10.2	16.4	12.8	20.5	1.9	3.0	15%	15%	38%
SOUTH DAKOTA	2.7	4.9	2.0	3.5	0.4	0.8	20%	23%	8%

for diffusion modeling.

Perhaps the most immediate use of the model is to provide a link between laboratory chamber studies and the real world environment. To this end, the model was run using environmental data from chamber studies (Hill 1973) and physiological damage data on alfalfa (Hanson 1972). Alfalfa was chosen for the test since it is both a sensitive species and one that may be used in the NGPRP to revegetate mined surfaces.

Chamber conditions were approximated with a ventilation speed of 2.5 m/sec, a temperature of 23°C, and an ambient SO_2 concentration of 500 $\mu g/m$. Vegetation damage in the chamber had been observed within a month with a 4-hour-per-day exposure. Our model -- equations (1) - (5) -- was run with these environmental conditions and indicated that saturation concentration, $\chi_{sat.}$, in the mesophyll was reached well within the 4 hours each day (in fact, within about 1 hour). The daily uptake so calculated was multiplied by 30 to give a monthly estimate.

Since damage was observed in the chamber, we assume that this amount of SO_2 uptake is sufficient to produce damage, at least for alfalfa. We will term this the damage uptake horizon (DUH). The DUH is approximately 48 x 10^{-8} μg per cubic centimeter of mesophyll water. The ratio of actual uptake to DUH is shown in Table 1.

To consider a single "worst case" we chose North Dakota vegetative and atmospheric estimates for the year 2000. An ambient concentration of 16 $\mu gm/m^3$ was taken following Fox (1976) for the maximum year 2000 scenario. Temperature was held constant at 6°C, as was the wind speed at 10 m/sec. The results of this calculation indicate that SO_2 uptake after 5 months is approximately 18 x 10^{-8} μg per cc of mesophyll water. While the ambient concentration between North Dakota and the environmental chamber differs by a factor of 30, uptake differs only by a factor of 2.5. This suggests that chamber studies may not be conservative in comparison with "worst case" environmental conditions.

CONCLUSIONS

The model presented here is a combined theoretical and empirical calculation which has not been fully validated. The individual equations have been validated, however. The use of the resistance analog, for example, is generally accepted.

Assumptions are made about many of the vegetation parameters, particularly for large area extrapolation and comparison with chamber studies. These may result in model estimates which are in error. In addition, sulfur

dioxide incorporation into the metabolic pathway represents the true removal mechanism, but it is not included in the present model. The problem of determining damage uptake horizon is extremely complex, since it depends on the sulfur status of plant and soil, and vegetation growth rates. For example, the difference in SO_2 uptake between the chamber and North Dakota vegetation may not be significant if coupled with information on sulfur status of the soil. The need for a soil model is evident.

The potential for vegetative removal of harmful pollutants has not been thoroughly explored. Murphy et al. (1975) have suggested that forests may have the potential to safely remove sulfur dioxide at low ambient concentration -- less than their damage threshold -- but the maximum level at which vegetation can safely remove pollutants is unknown (Neuberger 1963).

The model developed here is linear. It can accommodate additional input as information becomes available. The output yields information on regional vegetation uptake for sulfur dioxide. While it is clear that the development scenarios for the Northern Great Plains will add significant amounts of SO_2 to the ecosystem, we can not as yet provide any quantitative assessment of the effects. The model presented herein represents one of many steps toward this end.

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Sensitivity Analysis of Surface Deposition in a Numerical Model of Atmospheric Dispersion[1]

Jackie Lewis and Gene L. Wooldridge[2]

Abstract.--Profiles of height-dependent diffusion which accomodate site-specific diffusivities were produced. A numerical model was adapted to incorporate the profiles. The model represented three-dimensional steady-state advection and diffusion of aerosols from an elevated point source. Sorption effects were simulated with surface attachment coefficients greater than unity. This proved effective in depleting the plume differentially upward from the surface.

INTRODUCTION

Atmospheric dispersion models have been developed and refined in several forms over the past two decades, due to increased aerosol production and a heightened concern over the toxic effects of some aerosols on humans, animals, and plants. The models generally represent solutions of a differential equation which contains terms for advection and diffusion. The more basic solution in common use is the plume model, with a number of restrictive assumptions on atmospheric conditions.

The atmospheric turbulence near the ground differs significantly from the mesoscale eddy turbulence usually used for dispersion calculations (Pasquill 1974). Sutton (1953) recognized that constant eddy diffusivity is unacceptable in problems of diffusion in a turbulent atmosphere. Dispersion coefficients depend upon, among other factors, height above the surface, surface roughness, the scale of motion, and wind speed and fluctuations (Agee, et al. 1973). Diffusivity cannot be treated independent of height above the ground if the boundary layer flow in the first several hundred meters is to be represented. There exists no convenient method for determining the relationship between the aerodynamic roughness of the surface and the dispersion coefficients (Ragland and Dennis 1975). Estimates of diffusivities from Pasquill stability categories only give crude indications of the diffusion characteristics (Reiter 1973). Lettau (1973) concluded that eddy diffusivities are generally unique to any given experimental situation and have very little extrapolative value to other experimental situations.

Using superpressure mylar balloons, measurement of lateral and vertical diffusivities as functions of height can be made. From the tracking data, the coefficients are calculated as functions of the variance of the Lagrangian velocity components and Lagrangian time constants. Wooldridge and Orgill (1975) used this technique in the Eagle River Valley of Colorado. Wooldridge (1974) determined height profiles of diffusivities in Cache Valley of northern Utah from balloon data. Computations using measured diffusivities profiles for these two valleys showed concentration distributions quite different from each other (Wooldridge and Lewis 1975). Circulation separation between Cache Valley and the gradient wind above ridge lines was found by Ellis and Wooldridge (1973). Studies of diffusivities in valleys by Wooldridge (1974) and Wooldridge and Orgill (1975) demonstrate increasing K values throughout the valley to just above the ridge. This indicates that the entire valley is within the surface boundary layer and that the diffusivities probably decrease in the gradient flow above this point.

The general shape of the vertical distri-

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bution of diffusivity shows a local maximum of the diffusivity, K, near the top of the surface boundary layer (Blackadar 1962; Agee, et al. 1973; Egan and Mahoney 1972 ; Wipperman 1973; O'Brien 1970). The following exponential function was developed by Agee, et al. (1973),

$$K(z) = a[\exp(-bz/Z_T) - \exp(-bcz/Z_T)] \quad [1]$$

where a, b, and c are arbitrarily chosen parameters that primarily affect the magnitude of K, the height scale, and the ratio of the maximum diffusivity to the diffusivity at the top of the Ekman layer, respectively. Z_M is the height of the maximum diffusivity, Z_T is the top of the Ekman layer, and z is the height above the surface.

When c is greater than one in equation [1], as Agee, et al. said it should be, the resulting profile increases rapidly near the surface, changes more slowly as the top of the surface boundary layer is approached, then decreases upward. Wooldridge and Orgill (1975) measured diffusivity profiles in mountainous terrain that increased slowly near the surface and more rapidly from the middle to the top of the valley. Profiles that behave this way in the surface boundary layer can be produced with Agee's formulation if c is less than one. However, these profiles will not decrease above the surface boundary layer. Steady-state calculations within the valley, as in this study, are not affected by the shape of the profile above the valley.

A variety of processes remove aerosols from the atmosphere, although they are incompletely understood. Deposition by precipitation scavenging accounts for some removal, but it occurs infrequently in arid regions. Reaction, or sorption, with the soil or plants probably removes the largest percentage and should be considered as a major sink. The physics of particle-surface interactions is quite complicated. Natural surfaces may be good reflectors or good adsorbers, but rarely perfect. The exact behavior at the interface depends upon the properties of the surface and the diffusing particles (Csanady 1973).

Depending on the vegetation type, the area of leaf surface per unit area of ground may vary from a factor of two to a factor of ten. The cellular surface area surrounding the intercellular air spaces within the leaf is considerably higher than the leaf surface area (Hill 1971). Therefore, the effective adsorbing surface may be many times greater than the total surface area. Slade (1968) reported that Simpson (1961) computed deposition of 90% within 3200 meters of the source. Martin and Barber (1971) found a reduction of 75% in SO_2 between 15 and 50 cm above a hedge. Hill (1971) measured uptake of CO_2 and O_3 by alfalfa and oats in a laboratory chamber and in the field. He found it to vary from 86% to 95% depending upon the wind speed, canopy, and light. On soil with no plants the uptake was only 7% for dry soil and 19% for wet soil.

PROCEDURES

The starting point of most mathematical treatments of diffusion from sources is a generalization of the classical differential equation of heat conduction in a solid. Roberts (1923) gave the solution for the steady-state continuous point source as

$$\frac{\chi}{Q}(x,y,z) = \frac{1}{4\pi x(K_y K_z)^{1/2}} \exp\left[\frac{-\bar{U}}{4x}\left(\frac{y^2}{K_y} + \frac{z^2}{K_z}\right)\right], \quad [2]$$

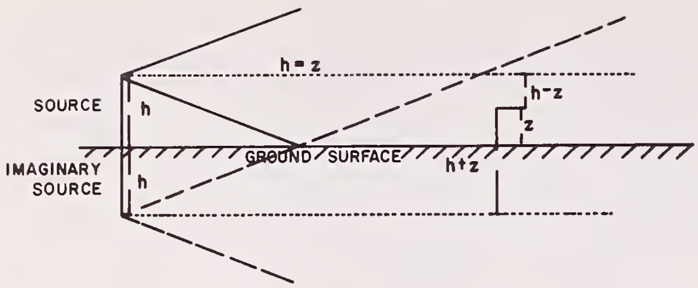
where Q is the source strength, χ is the local concentration, x, y, and z are rectangular coordinates (along-wind, crosswind, vertical), K_y and K_z are the crosswind and vertical diffusivity coefficients, respectively, and $\bar{U}$ is the mean wind speed. The current plume models now in use substitute $\sigma^2 = 2Kt$, where t is time and σ^2 is variance of an assumed Guassian distribution, in the above equations resulting in diffusion dependent upon downwind distance and independent of height.

The mathematical device which represents perfect reflecting boundaries is the introduction of "mirror-image" sources of strength equal to the source at its origin (Csanady 1973). Surface attachment is parameterized by multiplying each reflective term of the equation by $(1-\alpha)$, where α is an attachment coefficient. Using height-dependent diffusivities as determined by equation [1], assuming an incompressible fluid and neglecting diffusion along the wind, the equation for an elevated source becomes:

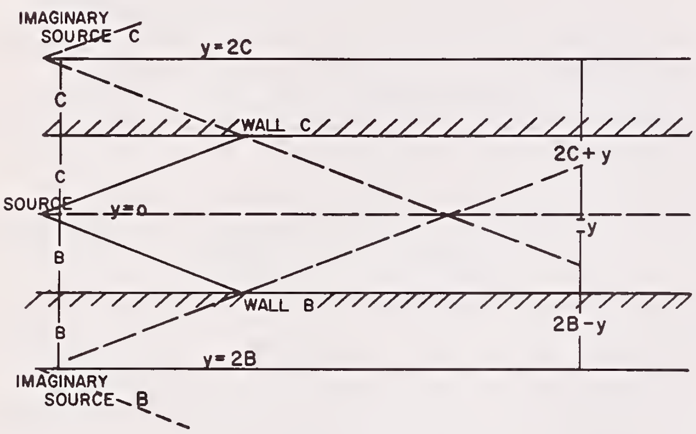
$$\frac{\chi}{Q}(x,y,z) = \frac{(K_y(z)K_z(z))^{-1/2}}{4\pi x}\left[\exp\left(\frac{-\bar{U}y^2}{4xK_y(z)}\right) + (1-\alpha)\left\{\exp\left(\frac{-\bar{U}(2C+y)^2}{4xK_y(z)}\right) + \exp\left(\frac{-\bar{U}(2B-y)^2}{4xK_y(z)}\right)\right\}\right] * \left[\exp\left(\frac{-\bar{U}(z-h)^2}{4xK_z(z)}\right) \div (1-\alpha)\exp\left(\frac{-\bar{U}(z+h)^2}{4xK_z(z)}\right)\right], \quad [3]$$

where B and C are the distances from the source to the farthest and closest valley walls, respectively. Figure 1 illustrates the mirror-image reflection from the surface and the two valley walls.

The topography simulated for this study



(a)



(b)

Figure 1. Simulated topography and ideal plume position for a continuous point source in a mountain valley. (a) side view, (b) top view.

was a long, narrow, symmetric valley with steep, sloping sides. The sloping walls were approximated in a step-like mode by increasing the distance from the valley center (y = 0) to the walls for each increase in height according to:

$$B = Y_t - B_t + z/\tan\phi. \quad [4]$$

The slope of the walls, ϕ, was 30° from horizontal; B_t is the distance from the source to the B wall at the top of the valley. Valley symmetry here allowed C equal to B. At ridge height (z = 1000 m) the half width of the valley, Y_t, was 2500 m. The valley floor was 767 m wide, flat and non-sloping. There were no obstructions to airflow within the valley as far as the calculations proceeded. A continuous point source was simulated 100 m above the ground and in the center of the valley. The mean wind along the valley was taken at 3 m sec^{-1}. All ground surfaces were assumed to be covered with vegetation.

For each diffusion profile a set of the constants a, b, and c is required. Agee, et al. (1973) obtained a solvable system for determining a, b, and c when the values of Z_M, Z_T, the maximum diffusivity, K_M, and the diffusivity at the top of the profile, K_T, are known. The height of the maximum diffusivity, Z_M, is taken to be above the ridge height at 1200 m, considered to be the top of the surface boundary layer. Because the top of the Ekman layer is likely to be found in a zone around twice the ridge height, 2400 m was taken as the top of the profile, Z_T, for this model. Values of a, b, c, K_M, and K_T are given in Table 1 for each of the diffusion profiles.

Table 1. Parameters for K_y and K_z profiles.

	K_{yI}	K_{zI}	K_{yII}	K_{zII}
a	2400.00	2000.00	-3559.00	4000.00
b	-1.95	-2.00	2.11	1.93
c	0.98	0.98	0.90	1.07
K_M	--	--	135.90	99.50
K_T	--	--	80.20	58.90

K_{yI} and K_{zI} represent the lateral and vertical diffusivities found in mountainous terrain while K_{yII} and K_{zII} are the profiles suggested by Agee, et al. The diffusivity profiles were obtained by calculating K(z) at each computational height. Diffusion at the surface was not allowed to go to zero as in equation [1]. The diffusivity was assumed to be constant from z = 10 m to the surface and equal to the value at 10 m. The diffusivities fit well into the range of the Pasquill estimations, and the resulting profiles are shown in Figure 2.

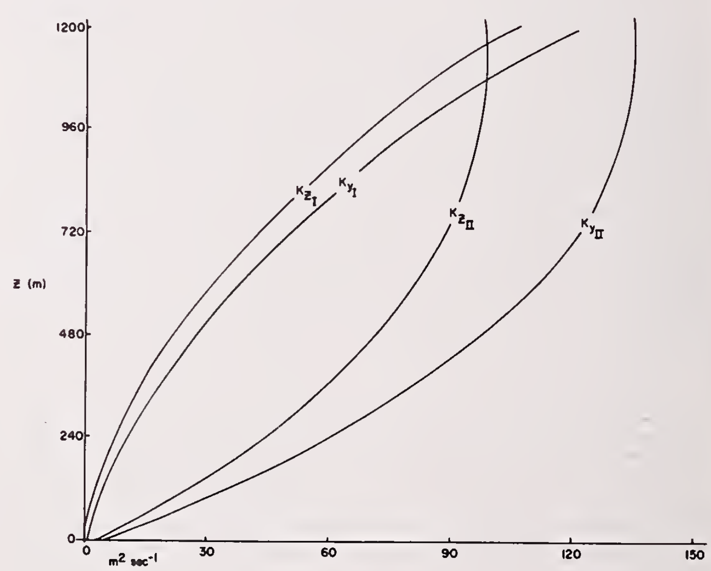


Figure 2. Diffusivity vs. height. K_z--vertical--component; Ky--horizontal component. Case I and Case II (refer to Table 1).

A perfectly reflecting boundary can be represented by equation [3] with $\alpha = 0$. At any given point in the grid the reflected amount represents a smaller percentage of the total concentration than the amount contributed by the original source. With $\alpha = 1$ there would be no reflection of plume material. The unreflected plume would still be within the surface layer and available for removal by the multiple-layered plant canopy. Further removal can be parameterized by increasing the value of α greater than 1. This would result in removal of not only the reflected amount, but some fraction of the original plume. Values of α between 0 and 1.5 were used in this study. The vegetation on all surfaces was assumed to have similar adsorption capabilities.

RESULTS AND DISCUSSION

The diagrams of normalized concentrations, figures 3-8, reveal a dramatic change in pattern when the profile suggested by Agee, et al. (1973) (case II) is modified through the use of b less than zero and c less than one. The plume centerline is no longer depressed toward the surface but remains near the original source (effective stack) height for distance up to or exceeding 10 km in a mountain valley. Further, the plume of case I does not spread laterally as quickly at low levels, due to the smaller values of K_{yI} computed there, while the case II plume is quite evenly distributed.

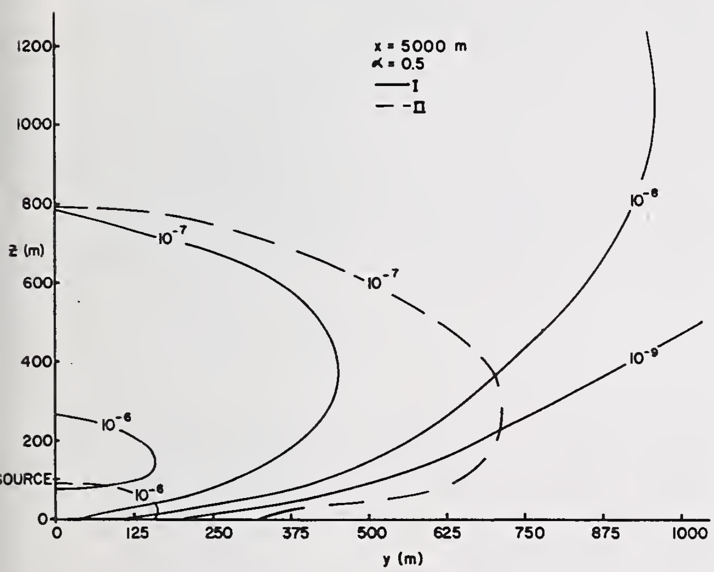


Figure 3. Isopleths of concentration. 5000 m downstream. $\alpha = 0.5$.

The diffusivity profiles used in the case I calculations more closely fit the profiles measured at Camp Hale, in the Rocky Mountain plateau of central Colorado (Wooldridge and Orgill 1975). Plume tracking by aircraft also

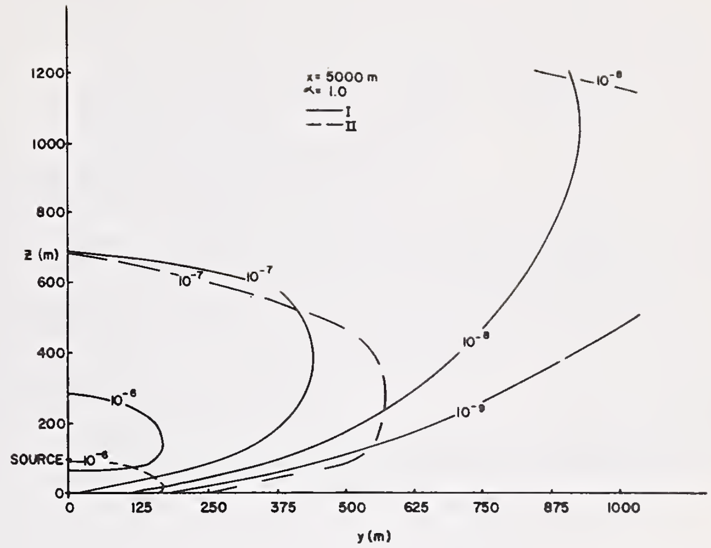


Figure 4. Same as 3 except $\alpha = 1.0$.

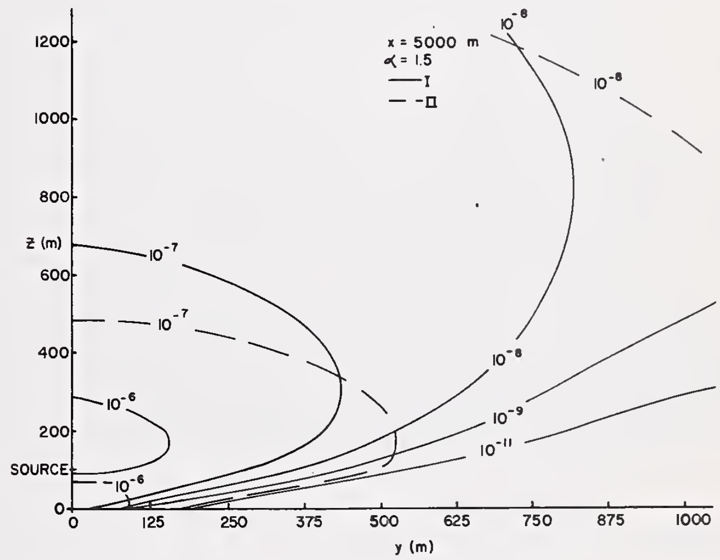


Figure 5. Same as 3 except $\alpha = 1.5$.

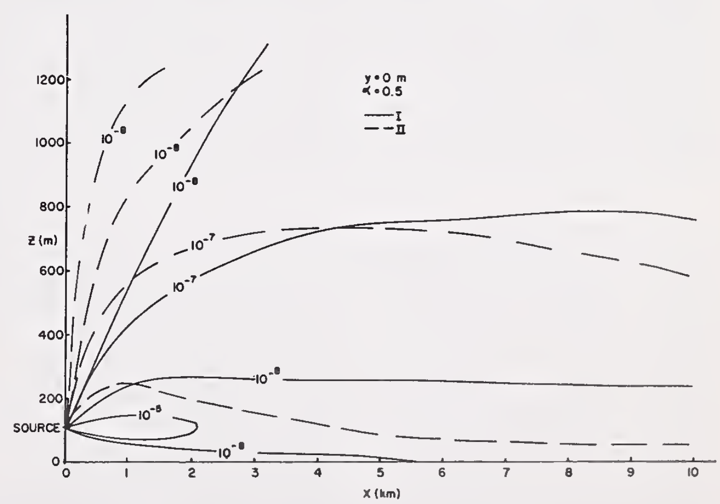


Figure 6. Isopleths of concentration along centerline. $\alpha = 0.5$.

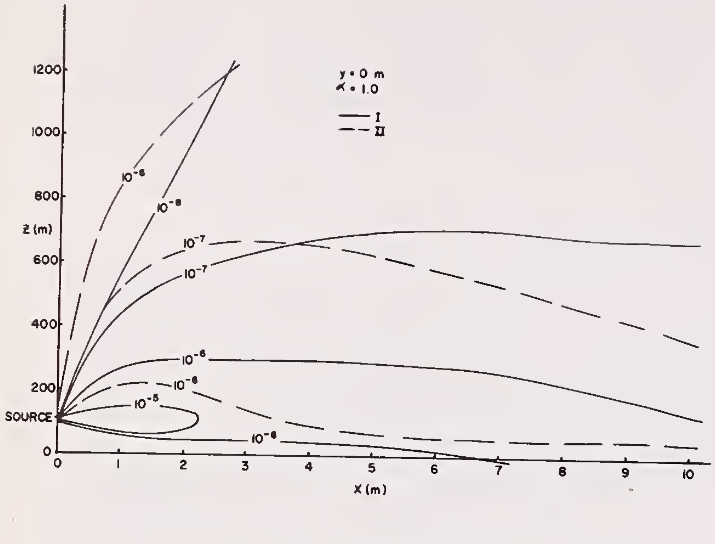


Figure 7. Same as 6 except α = 1.0.

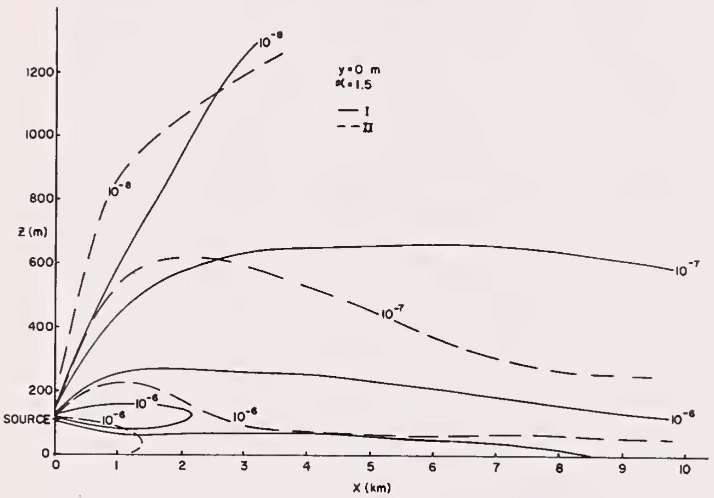


Figure 8. Same as 6 except α = 1.5.

suggests that the lowering of plume centerline as calculated with b greater than zero and c greater than one does not occur, either in mountain valleys or over less rugged terrain. Dispersion is better represented by site-specific diffusion than a generalized formulation.

The patterns of both sets of calculations change as the attachment coefficient, α, varies from partial attachment ($\alpha < 1$) to greater than unity. Near the source where the reflective terms have no influence the attachment coefficient makes little impact in the distribution. In the remaining airspace the attachment coefficient is most effective where the diffusion is greatest. Figures 3, 4 and 5 reveal a gradual decrease in the concentration of aerosols at the surface and in the airborne plume as α increases, with a greater effect in case II (note the change in the 10^{-7} isopleth). When α increases beyond one (Figure 7) the concentration near the ground toward the valley walls decreases by two orders of magnitude. The longitudinal sections (Figures 6, 7, and 8) also illustrate the effects of increasing α to higher values, with the concentration near the ground decreasing the most noticeably downwind from the source.

CONCLUSIONS

The practice of allowing an attachment coefficient to attain values greater than unity appears to simulate the enhancement of surface sorption by foliage, reducing aerosol concentrations in the plume well above the surface. The sensitivity of the model to attachment seems somewhat dependent upon the rate of the diffusion. This method should be further tested using field tracer experiments to determine appropriate values of α for various atmospheric conditions and foliage types, but this study suggests the feasibility of the technique for operational and investigative purposes.

The variation of aerosol concentration patterns as the diffusivity profile is changed emphasizes the significance of this factor in plume modeling for this study. The magnitude of the diffusivities at the top of the boundary layer, here estimated to occur slightly above the mountain ridge line, were approximately the same. The major difference in the two sets of profiles was the curvature within the valley (surface boundary layer). This stresses the need for more measurements of site-specific diffusivity profiles, particularly in rough terrain, before adequate dispersion modeling can be accomplished. The shape of the profile and the magnitude of the diffusivities must be determined over a range of meteorological regimes.

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Experimental Studies of Herbicide Drift Characteristics[1]

D. S. Renne and M. A. Wolf[2/]

A field study, utilizing a unique experimental design which monitored all the various components of herbicide drift, was undertaken by Battelle-Northwest on the Hanford Reservation in eastern Washington State during 1975 to study techniques for maximizing herbicide applications from a spray airplane on the intended area and minimizing drift. The results of these experiments have shown that the initial drift and drift deposit components for various application techniques varied by only a factor of two or so, depending on the production of smaller droplets. Meteorological conditions become increasingly important at greater downwind distances from the source. Furthermore, drift reduction was most effective under conditions of high relative humidities and cool temperatures. At large distances from the source, ground level drift was higher on stable than on unstable days.

INTRODUCTION

The use of chemical herbicides and pesticides to control broadleaf weeds and insects in crops and forest stands has been given increasing application in recent years by agriculturalists and foresters. However, the potential damage to nearby sensitive crops or to humans from the inadvertent drift of these chemicals beyond the intended area of application continues to be a serious problem, and has been given extensive study. Tests conducted in Arizona, for example, show that in general less than 50% of the intended aerial application of a pesticide is actually deposited on the target (Ware, et al., 1970). Other researchers have found that the drift component is roughly 3% of the intended application for ground rigs, and as much as 4-5 times that amount for aerial applications (Drummond, 1973; Frost, 1973). Atmospheric measurements of 2,4-D have shown that drift can extend well beyond the target area. Levels averaging 0.3 to 0.6 g-m^{-3} have been maintained for periods on the order of a month in the wheat producing regions of Saskatchewan and Washington (Peckenpaugh, et al., 1974; Que Hee, et al., 1975).

Numerous studies to determine techniques to reduce the drift component from aerial and ground-rig applications have been undertaken. These studies have shown that meteorological conditions, particularly atmospheric turbulence and the near-surface relative humidity and air temperature, greatly affect the drift component, with the larger drift residues observed under stable, dry atmospheric conditions (e.g., Yates and Akesson, 1966). These researchers have also experimented with a variety of nozzle configurations and spray viscosities and have shown that drift residues can be decreased by about a factor of two by attempting to eliminate the finer droplets and increasing the viscosity of the mixture (e.g., Kaupke and Yates, 1966). However, a major short-coming of most of these studies is that only one component of the drift, usually the drift residues or downwind depositions, was measured. Unless all material is accounted for as deposition, the drift component can not be determined without additional air concentration measurements, both along the surface downwind from the source and in the vertical.

Hypothesizing that all the components of drift (ground level and vertical exposure and surface deposition) need be measured simultaneously to determine effective drift control techniques, Battelle-Northwest conducted field experiments during the summer of 1975. All the components of various aerial applications of 2,4-D herbicide on target and down-

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wind of the target area under differing environmental conditions and for a variety of spray nozzle configurations and herbicide concentrations were measured. The ultimate goal of experiments such as these is to utilize the information to optimize the use of 2,4-D so that effective weed control and substantial reduction in the drift component can be achieved. Although these experiments were designed primarily for agricultural applications, the results can be applied to forestry uses, where the characteristics of the drift component over a forest canopy from aerial applications of insecticides must be understood.

EXPERIMENTAL OBSERVATIONS

Experimental Site

The 2,4-D drift and deposition experiments were conducted at a site approximately 40 km northwest of Richland, Washington on the Hanford Reservation. This facility is operated by the United States Energy Research and Development Administration. The site is a portion of the Hanford diffusion grid, and is characterized by relatively flat, sagebrush covered land at an elevation of about 220 meters above sea level.

A permanent 62 meter tower on the Hanford diffusion grid was incorporated into the 2,4-D experimental site. This tower is 1600 meters to the east of the Hanford Meteorological Station (HMS) 125 meter tower, and 225 meters to the east of the spray aircraft flight path.

Field Equipment

The deposition of 2,4-D was sampled at 30 locations in the target area and at eight additional points downwind of the target area, including the tower location. Air samplers were also positioned at the same eight downwind points, with an additional nine samplers located at ten levels on the 62 meter tower.

The deposition jars in the target area were divided into two lines, one 20 meters to the north of the downwind array, and the other along the same line as the array. Each line of target area deposition samplers consisted of 15 jars located three meters apart. The eight downwind samplers were spaced 25 meters apart, with the first sampler located 25 meters downwind of the spray aircraft flight path. The vertical air samplers were spaced in a logarithmic fashion ranging from 0.39 to 62.0 meters above the ground. A schematic of the sampling array is shown in Figure 1.

The 1,500 meter flight path was oriented 18° from normal to the array. This was approximately normal to the predominant wind direction which, during the early morning hours of the summer season, is from 270° to 290°. The length of the flight path was chosen to assure that the tower samples were not subjected to the "edge effects" of the drifting cloud; i.e., they effectively would be sampling an infinite instantaneous line source.

Operations

A Piper Pawnee spray airplane was provided by the USDA Agricultural Research Service for this study. A unique feature of the aircraft was the capability to make two different applications of 2,4-D within a 5-minute period. This was possible because the aircraft is equipped with two separate systems of tanks, pumps and booms. This capability was utilized in this study by making a standard or "fixed" application from one system and a comparative or "test" application from the other. A single set of samples was exposed during the release and passage of both 2,4-D applications. They were quantified separately in the laboratory analysis phase. The meteorological conditions were assumed to be nearly identical for the two applications due to the short time period between releases. Thus significant observed differences in the drift between the two releases could be attributed principally to the spray nozzle configuration and the concentration of the chemical herbicide. Furthermore, comparison of the fixed application drift measurements for the several days helped identify and quantify the important meteorological effects.

Two commercially available low-volatile herbicides were chosen as tracers for this study, each of which can be quantified independently on a single sampler. The fixed application was 2.8 cc-m^{-2} (3 gal-acre^{-1}) of water containing 30 mg-cc^{-1} (0.25 lb-gal^{-1}) acid equivalent of a butoxyethanol ester (BE).

The tracer utilized to test various configurations was a propylene glycol butyl ether ester (PGBE). The intention was to release the PGBE from different types of nozzles and with different concentrations to provide information on which application techniques reduced the drift component.

Four experiments, conducted in the daylight hours prior to 0700 PDT, under conditions of light winds, are studied here. Table 1 provides information on these tests, including the important differences between each of the PGE test applications and the BE fixed application.

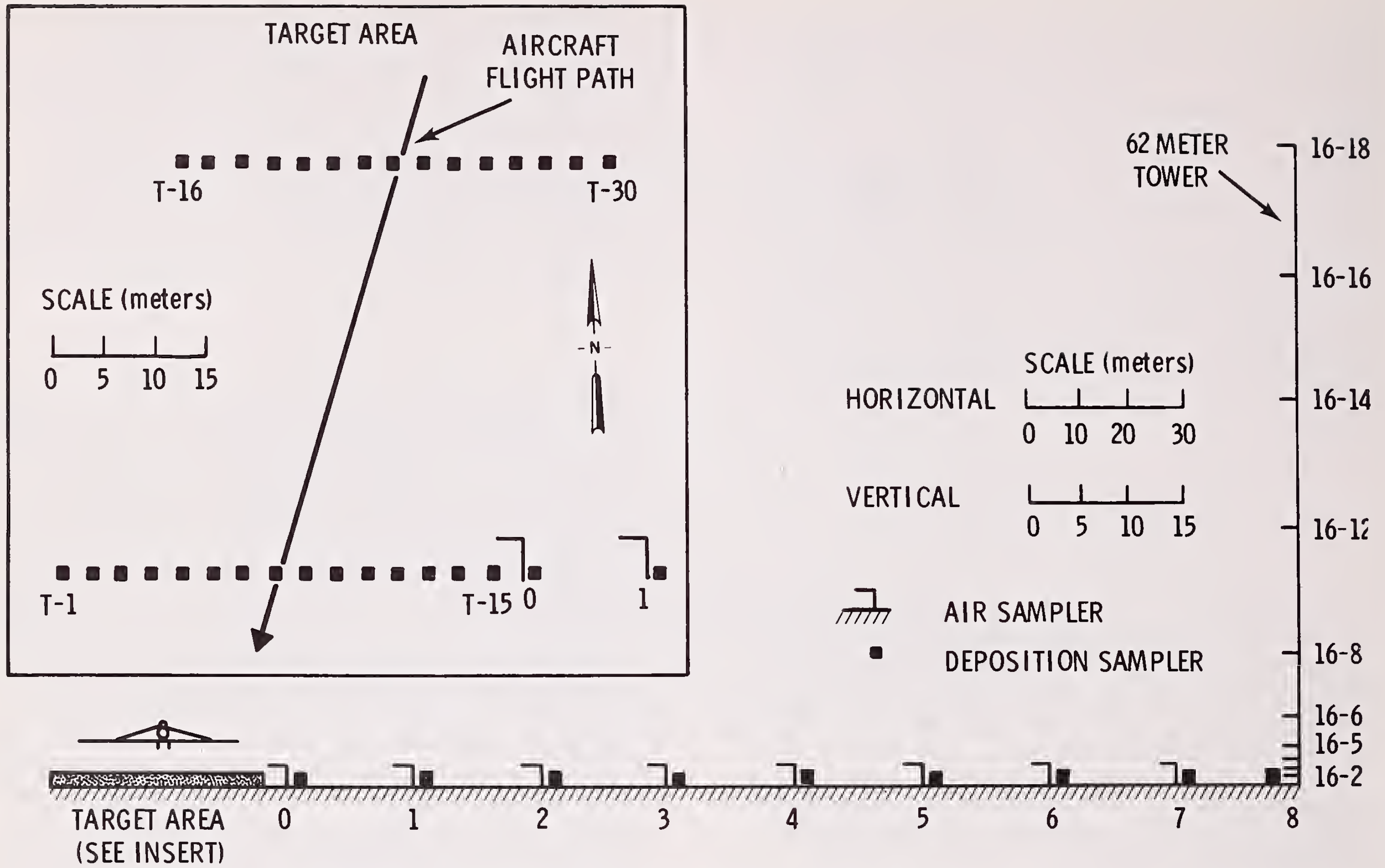

Figure 1. Schematic of Runs 5 - 7 Experimental Array

Table 1. Summary of 2,4-D Drift Experiment Tests

Run	Date	Local Time	Varations in Nozzle Configuration and Concentrations from Fixed Application
1	July 10	0650	None
2	Aug. 19	0622	Application rate: 1 gal-acre^{-1} (0.93 cc-m^{-2}) 25 nozzles, type D5/45
3	Sept. 3	0640	Application rate: Same as control 35 nozzles, type D5/no core; attitude angle 135° back (downward)
4	Sept. 16	0647	Application rate: 5 gal-acre^{-1} (4.7 cc-m^{-2}) 31 nozzles, type D8/46

All four runs were designed to compare various drop size spectrums caused by variations in operational techniques: low volume application per acre (Run 2), no swirl plate and steeper nozzle angle (Run 3), and high volume application per acre (Run 4).

RESULTS

Ground Level Drift

Figures 2 and 3 show distributions of ground level drift downwind of the source for the fixed and test application, respectively. Least squares lines of best fit were computed for each run and are included in the figures. In addition, a stability factor, F, was defined, following previous investigations (Yeo and Thompson, 1953):

$$F = \frac{T_{15} - T_2 - \Gamma \Delta H_{15-2}}{\bar{u}^2} \qquad (1)$$

where: T_{15} = temperature at 15 meters above the ground, °C

T_2 = temperature at 2 meters above the ground, °C

Γ = dry adiabatic lapse rate = -0.01 °C-m^{-1}

ΔH = distance between upper and lower temperature levels, m

$\bar{u}$ = mean wind speed between 2 and 15 meters above the ground, m-sec^{-1}.

The stability factors were computed from the HMS tower data at the time of the herbicide releases. A negative factor indicates an unstable atmosphere, and a positive factor a stable atmosphere.

Figure 2 shows that application of the same herbicide tracer applied in an identical manner on different days differed greatly due to different meteorological conditions. There are large differences in the slopes occurring for the cooler, more humid days when the droplets experience less evaporation and fall out faster, thus depleting the drifting plume. If these lines were to be extrapolated to distances well beyond 200 meters, then it is evident that large differences in drift would occur for different meteorological conditions.

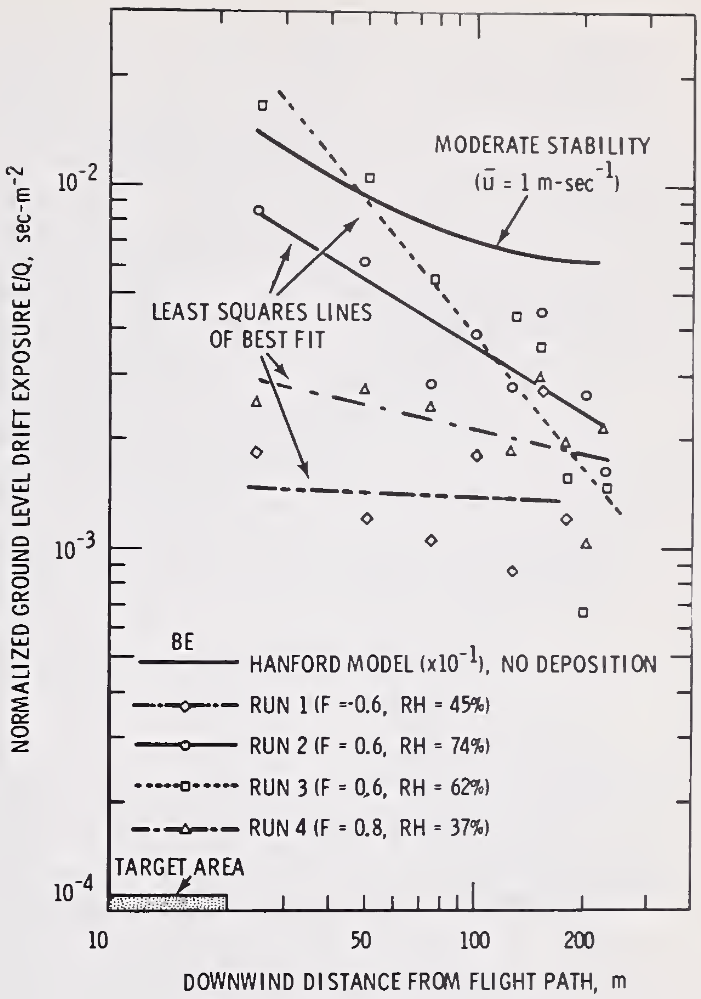

Figure 2. Normalized Ground Level Drift Exposures vs. Downwind Distance from Flight Path, Fixed Application of BE.

The test application drift characteristics shown in Figure 3 do not coincide with those of the fixed application. This is due to the effect of the differences in the way the PGBE ester was released from the spray aircraft. But again the slopes of the lines become the dominating influence in displaying drift reduction beyond 200 meters, indicating the importance of meteorological conditions in controlling drift. The different mechanical techniques tested to control drift resulted in variations of only a factor of two or so in the drift component. This is well within the sampling accuracy limitations of the experiment. However, the differences in slopes of the drift characteristics patterns between warm, dry days and cool, moist days result in substantial differences in ground level drift at large distances from the source. Thus, beyond 200 meters from the source meteorological conditions appear to be the dominant factor in controlling drift, and the manner in which the material is released from the aircraft, although still important, becomes a

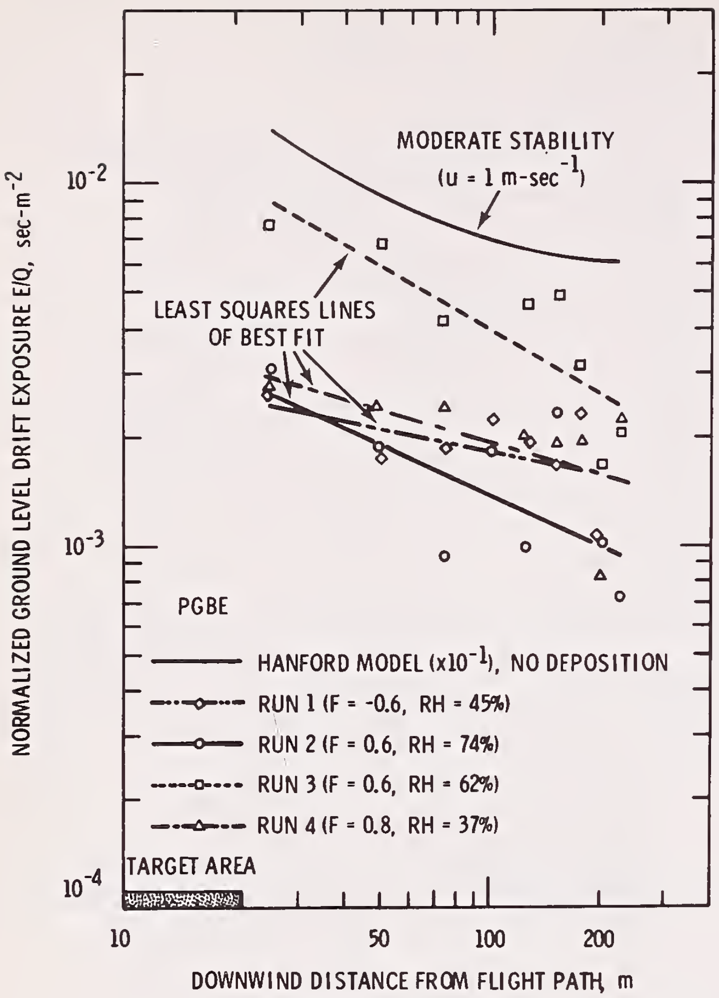

Figure 3. Normalized Ground Level Drift Exposures vs. Downwind Distance from Flight Path, Test Application of PGBE.

secondary factor. In particular, drift reduction is best on cool, moist days when evaporation of the droplets is minimized and their fallout at distances within 200 meters from the source is facilitated.

A curve representing the Hanford diffusion model for moderately stable conditions with 1 m-sec^{-1} wind speeds and an aircraft height of 5 meters above the ground is included in the figures. This model is representative of a nondepositing instantaneous infinite line source plume and is discussed in detail by Slade (1968).

In Figures 2 and 3 the curves of the Hanford model have been reduced by a factor of ten to coincide roughly with the actual drift characteristic values. When comparing the slopes of the nondepositing theoretical curve with those of the depositing observed drift characteristics, it is evident that deposition is much higher on cool, moist days when evaporation of the droplets is suppressed.

Drift Deposits

Figures 4 and 5 show the distribution of downwind drift deposits normalized to the aircraft release rates for Runs 2 through 4 (drift deposits were not obtained for Run 1). The fixed application drift deposits for Runs 2 and 3, which were cool, moist stable days, show striking similarities to each other, and beyond about 75 meters from the source show substantially less drift deposits than Run 4, which was a warm, dry day. Again this indicates the significance of meteorological conditions for controlling drift deposits, particularly at the larger distances from the source.

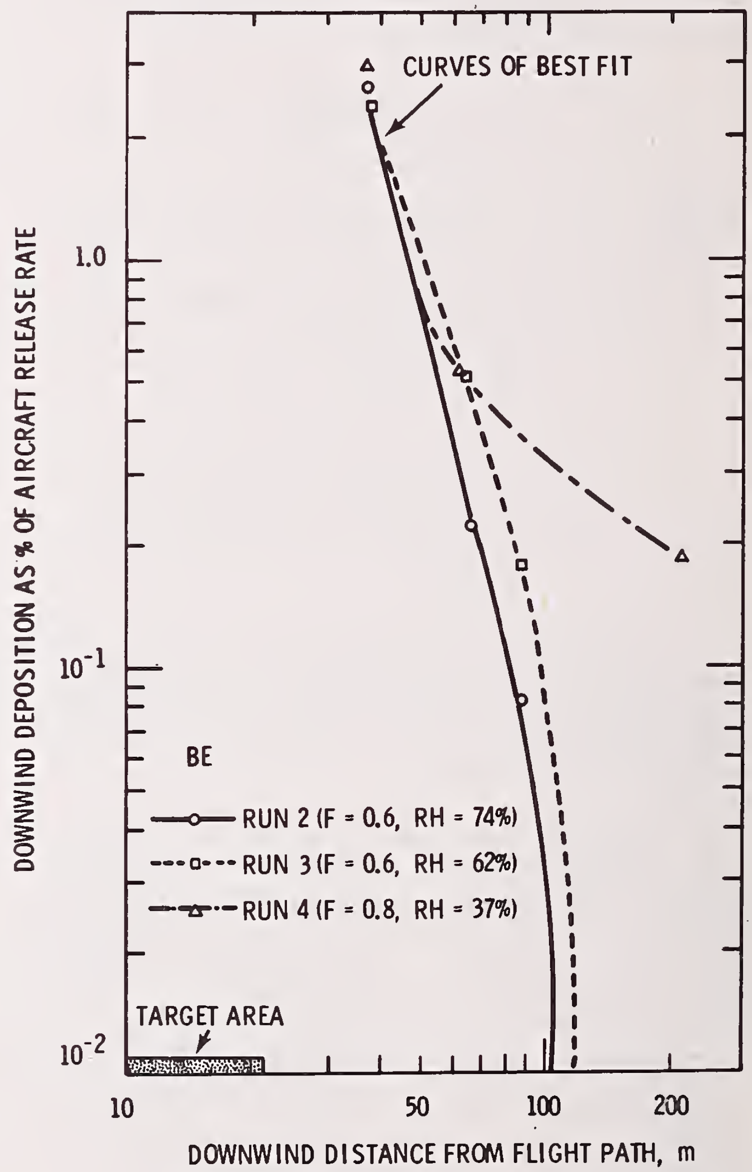

Figure 4. Normalized Drift Deposits vs. Downwind Distance from Flight Path, Fixed Application of BE.

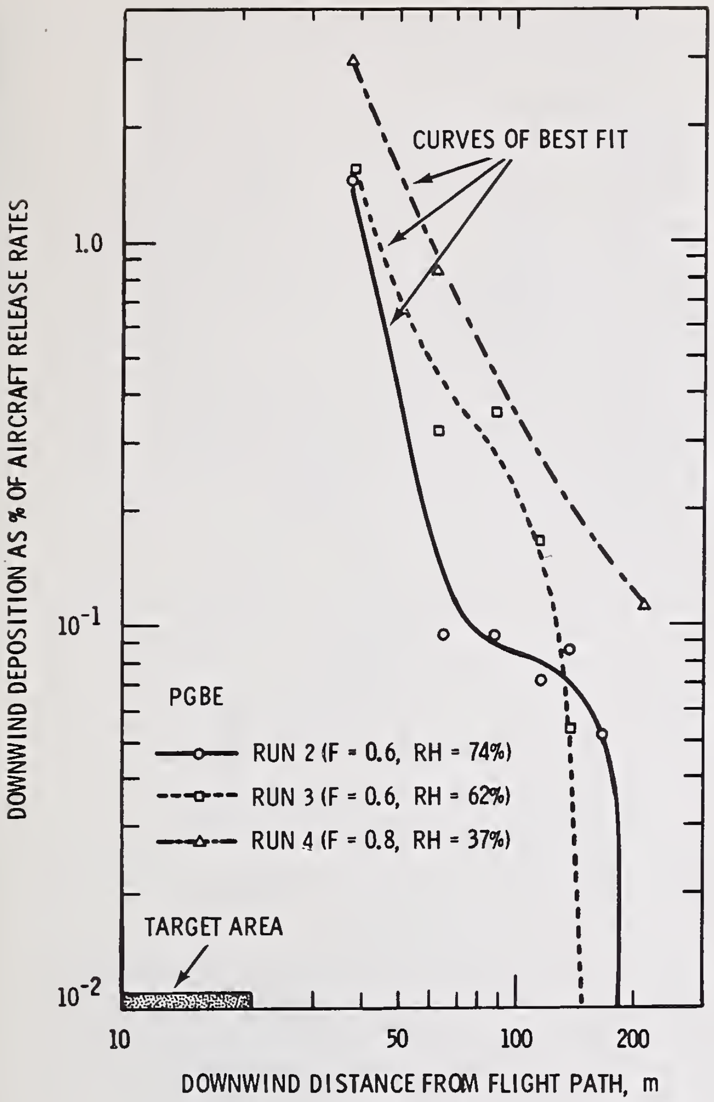

Figure 5. Normalized Drift Deposits vs. Downwind Distance from Flight Path, Test Application of PGBE.

The drift deposit characteristics for the test applications are similar to the fixed applications with the exception of a delayed deposition indicated by the slight "humps" in the curves between 75 and 100 meters for Runs 2 and 3. This delayed deposition can be due to a slightly different droplet size distribution from the fixed application technique, indicating the effect of different mechanical modes for releasing the material. Since these two runs were on cool, moist mornings, less evaporation is occurring and the smaller droplet spectrum that results in this delayed deposition characteristic is not suppressed. Run 4, which was a warm, dry morning, suggesting greater evaporation, does not show this characteristic, indicating that the smaller droplets have already evaporated. Nevertheless, drift deposits are higher in general for that day since the total drift is higher.

These curves suggest a bimodal type of droplet size distribution resulting from the various types of release of the herbicide. The primary distribution consists of the larger droplets, the size that are produced purposefully to assure application of the herbicide on the intended area. However, a secondary distribution results from the breakup of the solution as it is released and from evaporation of the larger drops. This distribution consists of finer particles whose fallout is delayed due to lower settling velocities. Figures 4 and 5, as well as Figures 2 and 3, suggest that this droplet size spectrum can be controlled somewhat by the manner in which the herbicide is released from the aircraft, but that beyond 100 meters or so meteorological conditions become the primary influence on drift and drift deposit characteristics.

Deposition Velocities

Although the same conclusions can be drawn from the analyses in each of the previous two sections, some question remains as to the effectiveness of determining total drift from deposition samplers alone, as previous investigators have attempted. The evidence from Figures 2, 3, 4 and 5 indicates that air samplers are much more sensitive to drift than deposition jars for the release rates used here, and therefore provide more complete definition of the ground level drift. But more quantitatively, determining drift characteristics from deposition measurements requires knowledge of the relationship between drift and deposition. If this relationship is constant, inference on drift characteristics from deposition measurements can be made with reasonable certainty. However if the relationship between these two parameters is variable, characteristics of drift can be inferred erroneously from deposition measurements.

The relationship between drift and deposition can be expressed in terms of the deposition velocity:

$$V_d = 100 \left(\frac{D_f}{E}\right) \qquad (2)$$

where: V_d = deposition velocity, cm-sec^{-1}
D_f = deposition flux, g-m^{-2}
E = ground level air exposure, g-sec-m^{-3}.

Deposition velicities were computed from the drift and deposition data obtained in Runs 2 through 4 and are shown in Figure 6 for the BE releases and Figure 7 for the PGBE releases. The deposition velocity characteristics are

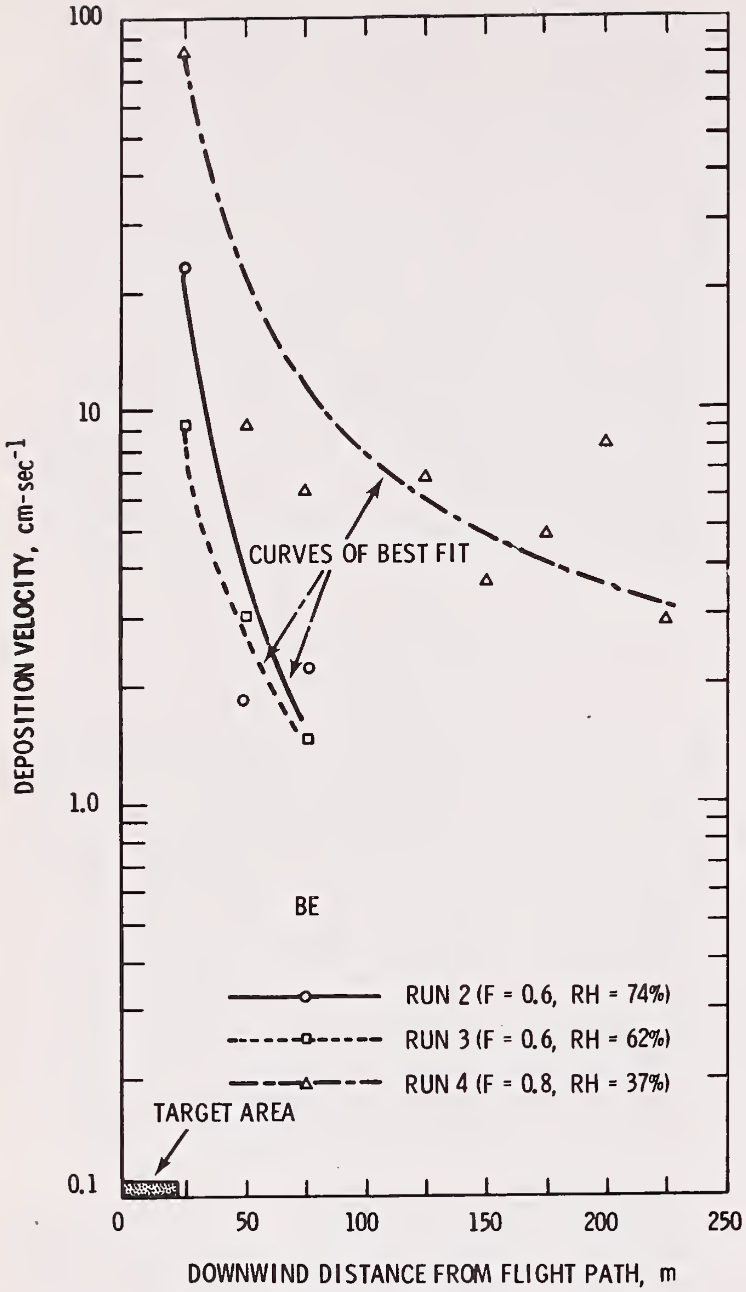

Figure 6. Downwind Deposition Velocities, Fixed Application of BE.

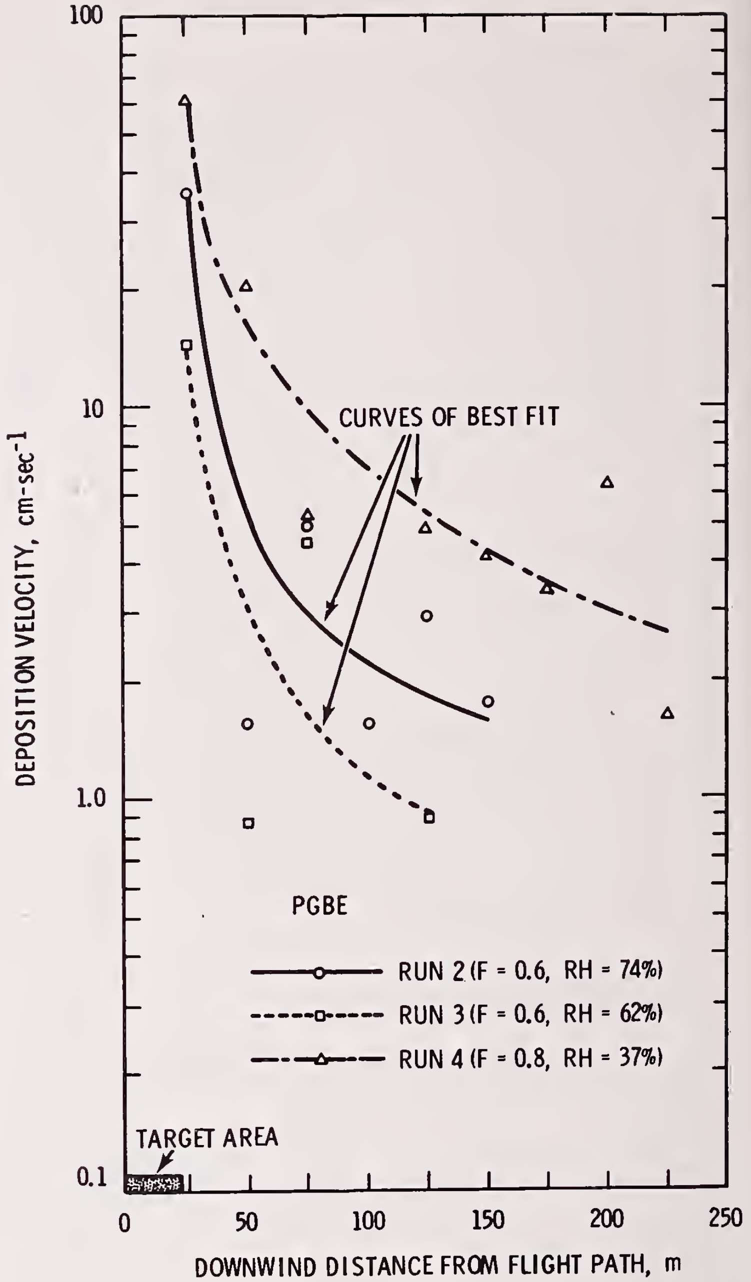

Figure 7. Downwind Deposition Velocities, Test Application of PGBE.

highly variable within 200 meters of the source, indicating the presence of a significant amount of larger droplets in the drift downwind of the target area. Thus for the size of the array used in these experiments inferring drift from deposition alone could result in erroneous conclusions with regard to methods to control drift.

The curves also show that once a sufficient distance is reached from the source the deposition velocity would probably reach a steady-state value of approximately 1 $cm\text{-}sec^{-1}$. This value appears reasonable in light of other investigations undertaken on the Hanford Reservation (Slade, 1968).

CONCLUSIONS

A number of different hypotheses with regard to reducing herbicide drift from spray airplanes using various nozzle sizes and orientation, and by spraying under different environmental conditions, have been tested under a pilot field experiment in eastern Washington. Although the results of these tests can only be regarded as preliminary until a more complete set of experimental information has been obtained, the major conclusions of these experiments are:

1. The combined deposition and air sampler approach is superior because all the material is accountable. Inferring drift only from downwind deposition measurements can provide inaccurate information due to sampling errors, the influence of vegetation on the samplers, and the large observed variations in deposition velocities within 200 meters of the source. Without the vertical resolution of air concentrations obtained from the tower samplers (measured during the experiments but not discussed here) a large drift component could go unnoticed if it were elevated above the surface air samplers.

2. The initial drift and drift deposit components varied by only a factor of two or so, depending on the production of smaller droplets, as various techniques were used to put the herbicide down from the aircraft. Meteorological conditions become increasingly important at greater downwind distances from the source since they affect the manner in which these smaller droplets drift downwind, deposit, and evaporate.

3. These experiments suggest that, for purposes of reducing herbicide drift, applications on cool, humid days act to suppress the evaporation of the droplets and allow the material to deposit more quickly, thereby reducing drift.

4. Drift and drift deposit characteristics of the fixed applications using a low volatile butoxyethanol ester (BE) tracer varied according to meteorology, but test applications of low volatile propylene glycol butyl ether ester (PGBE) using various spray nozzle configurations did not vary in the same manner as the test applications. Differences may be attributed to changes in the drop size spectrum between the fixed and test applications, or to variabilities in micrometeorological conditions between releases.

ACKNOWLEDGMENTS

The cooperation of the Agricultural Research Station, U. S. Department of Agriculture, Yakima, Washington, and in particular Mr. Robert Winterfeld, pilot of the spray airplane utilized in this research, is greatly appreciated. This research was conducted under Contract TDO-730 from the Pacific Northwest Regional Commission.

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Smoke Dispersal from a Controlled Fire Over a Logged Pine Forest Area[1;2]

C. E. Murphy, Jr., J. T. Sigmon,[3]
D. T. Williams, P. W. Ryan, and W. H. McNab[4]

Abstract.--The dispersion of smoke in the atmosphere was studied during a controlled fire of forest debris. An instrumented aircraft measured smoke density and other parameters in multiple traverses through the smoke plume. The data permitted contour maps of constant smoke density to be drawn in three dimensions. Centerline smoke density reached a maximum of 0.43 $\mu g/m^3$. Supporting meteorological data were taken at an array of towers (7 towers, each 62 meters high) near the fire, and at different elevations on a TV tower (400 meters high) located 35 km from the site of the fire. The data will permit the testing of mathematical models for the prediction of the dispersion of pollutants in the atmosphere.

Smoke patterns from a fire were measured with an instrumented aircraft. The objectives of the research were to (1) provide a data base for testing models of smoke dispersion, and (2) improve our understanding and prediction capabilities for dispersion of atmospheric pollutants in general. This paper discusses the experimental data. A later paper will discuss the suitability of models for predicting dispersion.

Site Description

The topography of the control burn area is moderately hilly with an elevation change of about 15 m from the highest to lowest point. The area had been covered with an even-age pine stand which was harvested by clear-cutting a few months before the fire. The soil is sandy through most of the area, and drainage of moisture proceeds rapidly after rainfall. This promotes rapid drying of forest fuels. There was no measurable rainfall in the three-day period preceding the fire; however, the relative humidity was high. On the day of the fire the minimum humidity was 42%. The high temperature for the day was 22°C. The mass of fuel on the ground before burning was estimated to be 32.5 metric tons per hectare. The fuels consisted of 23.3 metric tons per hectare of logging slash and 9.2 metric tons per hectare of forest floor litter. Post burn measurements indicate that 5.6 tons per hectare of logging slash and 6.1 metric tons per hectare of forest floor litter were consumed during the fire. The area burned by the fire was 15 hectares.

Meteorology and Climatology

Climatology data were available from a weather station maintained on the Savannah River Plant site by the Savannah River Laboratory, and from the U.S. Weather Bureau station at Bush Field in Augusta, Georgia. Mesoscale meteorological information was available for the period of the fire from a network consisting of an instrumented 400-meter TV tower and seven instrumented 62-meter towers. The nearest tower of the seven-tower system is approximately 4 km from the site of the fire. The TV tower is located approximately 35 km from the site of the fire. The instruments are scanned by a computer-controlled data acquisition system and stored on tape. The system can be interrogated at any time and will produce a map with the wind vectors from the seven

[1] Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, Nov. 16-18, 1976.

[2] The information contained in this article was developed during the course of work under Contract No. AT(07-2)-1 with the U.S. Energy Research and Development Administration.

[3] Savannah River Laboratory, E. I. du Pont de Nemours and Co., Aiken, South Carolina, and Duke University, Durham, North Carolina, respectively.

[4] Southern Forest Fire Laboratory, U.S. Forest Service, Macon, Georgia.

tower system and the temperature profile from the TV tower. The TV tower is instrumented to measure wind speed, horizontal wind direction, vertical wind direction, and temperature at seven levels from 10 to 330 meters. The instrumentation is capable of taking data with sufficient accuracy and time response to monitor the turbulent characteristics of the atmosphere as they relate to dispersion (see Crawford 1974 for more detail). Table 1 shows an example of the data available for a time period during the controlled fire.

Aircraft Data Acquisition

Measurements of smoke dispersal were made by flying transects through the smoke plume with an instrumented aircraft. The aircraft was a Martin-404 flown by EG&G, Inc., of Las Vegas, Nevada. The aircraft instruments recorded the following information:

- Greenwich time
- analog output of an epsilon meter, which provided a measure of atmospheric turbulence
- distance from two base points A and B measured by a microwave range system
- wind speed
- wind direction
- radar altitude
- pressure altitude
- air temperature
- dew point temperature
- air speed
- absolute air pressure
- analog output of nephelometer, which provided a measure of the smoke density

Table 1.--An example of the TV tower and seven tower system output averaged over the period 14:05-14:15 EST

	TV Tower						
Height (m)	2	10	36	91	137	243	335
Temperature (°C)	20.7	20.0	*a*	18.8	18.4	17.5	16.5
σ_T	0.2	0.2	*a*	0.1	0.1	0.1	0.1
Height (m)	10	36	91	137	182	243	304
Wind speed (m/s)	1.9	2.6	*a*	*a*	3.0	2.5	1.9
σ_s	0.6	0.6	*a*	*a*	0.7	0.7	1.2
Azimuth (°)	201	198	200	205	205	210	205
σ_a	22.6	13.6	13.0	12.5	13.2	15.5	12.4
Elevation (°)	-1	+5	-6	*a*	*a*	-12	*a*
σ_e	11.4	12.3	12.5	*a*	*a*	15.8	*a*
	Seven Tower System						
Location	A62	C62	D62	K62	F62	H62[b]	P62
Wind speed (m/s)	2.1	2.0	*a*	*a*	3.3	2.0	1.2
σ_s	0.5	0.9	*a*	*a*	0.8	0.7	1.0
Azimuth (°)	239	171	225	*a*	238	179	204
σ_a	25.2	14.4	25.6	*a*	42.0	17.2	49.2
Elevation (°)	52	58	62	120	51	58	67
σ_e	15.8	15.7	10.8	10.0	19.6	12.7	25.8

σ_T = standard deviation of temperature measurements

σ_s = standard deviation of wind speed measurements

σ_a = standard deviation of azimuth measurements

σ_e = standard deviation of elevation measurements

a. data missing or of poor quality.

b. tower nearest fire location.

Measurements were made at one-second intervals and stored on magnetic tape. The aircraft had an average speed of 90 m/sec. The flight pattern of the aircraft was designed to define the plume in three dimensions. Flight passes at 90° to the wind direction were made at altitudes above ground of 160, 400, 500, 725, and 850 meters 1.6 km downwind from the fire. The time of the flights were 14:00, 14:05, 14:09, 14:13, and 14:17, respectively. Passes were made 8 km downwind at the visible base and top of the plume. Passes were also made along the length of the plume, one pass above the visible centerline and one pass along each edge of the plume.

The aircraft was equipped with a multi-spectral photographic system which included an infrared scanner. Photographs and infrared scans were taken over the fire to determine visible plume width and an estimate of the area of fire.

Infrared Scans and Color Photography

Data from the aerial infrared scans (Figure 1) showed the progress of the fire. The fire was started at 13:15 EST December 5 as a backfire and then the entire area was fired from the edge. The infrared scans indicate that the north end of the fire burned first, and was noticeably cooler by the time the rest of the area was burning. Similar patterns could be seen from color photographs at the initial stages of the fire but were later obscured by smoke. The area had completely burned over by 16:30 EST but continued to smolder through that night.

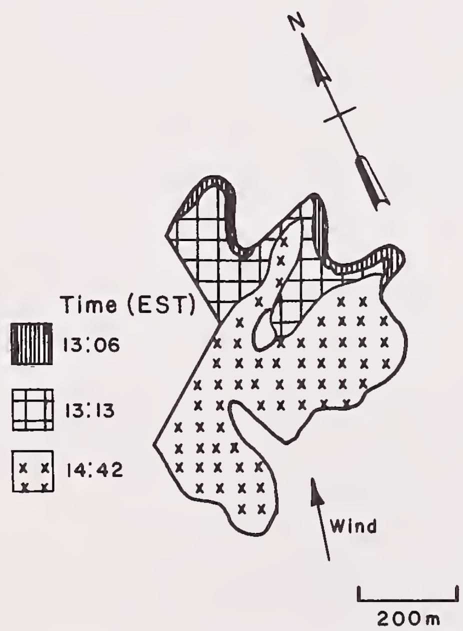

Figure 1.--Map of the burned area showing how the fire progressed. Data were obtained with an infrared scanner at the times indicated.

Climatological and Meteorological Observations

The wind speed aloft averaged 2.5 m/sec at an azimuth of 180-240°. The entire period was characterized by surprisingly persistent wind. Table 2 shows selected values of the standard deviations of the wind azimuth angle and elevation angle during the period of the controlled fire. The temperature profile of the TV tower and the standard deviation of the wind azimuth and elevation angle indicate unstable atmospheric conditions which favor dispersion of the plume.

Table 2.--Selected values of meteorological parameters from the 62 meter tower nearest the fire

Time	σ_e	σ_a	Azimuth, degrees	Wind Speed, m/s
14:00	14.8	21.5	239	2.0
14:15	12.7	17.2	179	2.0
14:30	12.9	14.4	201	2.0
14:45	17.1	34.2	182	1.2
15:00	10.8	23.5	227	1.7
15:15	9.9	16.3	218	2.2

Flight Data

The first step of data analysis was to scale the input parameters in meaningful units. Most of the parameters were prescaled by the data acquisition system and required only changes to consistent metric units. The nephelometer output was scaled by the equation

$$\chi = 38\ S\ (V - B) \tag{1}$$

where

χ = mass per volume of air ($\mu g/m^3$)

S = one of three scale factors for the nephelometer

V = instrument voltage (0-5 v)

B = background signal (0.08 v).

Figure 2 shows the output of the epsilon meter, the air temperature, the pressure altitude, and the nephelometer. The effect of the presence of the plume is seen in the increase in turbulence registered by the epsilon meter, the increase in air temperature, and the increase in the density of smoke as measured by the nephelometer. The displacements in the peaks of the turbulence, temperature, and density of smoke are most likely to have been caused by the different response times of the instruments.

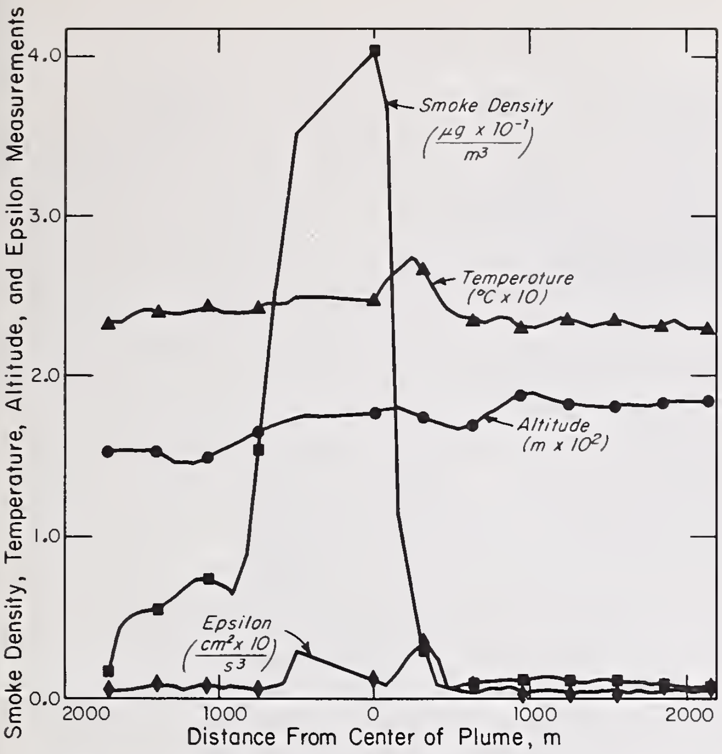

Figure 2.--Smoke plume data at an altitude of 160 meters for a flight path perpendicular to the wind direction.

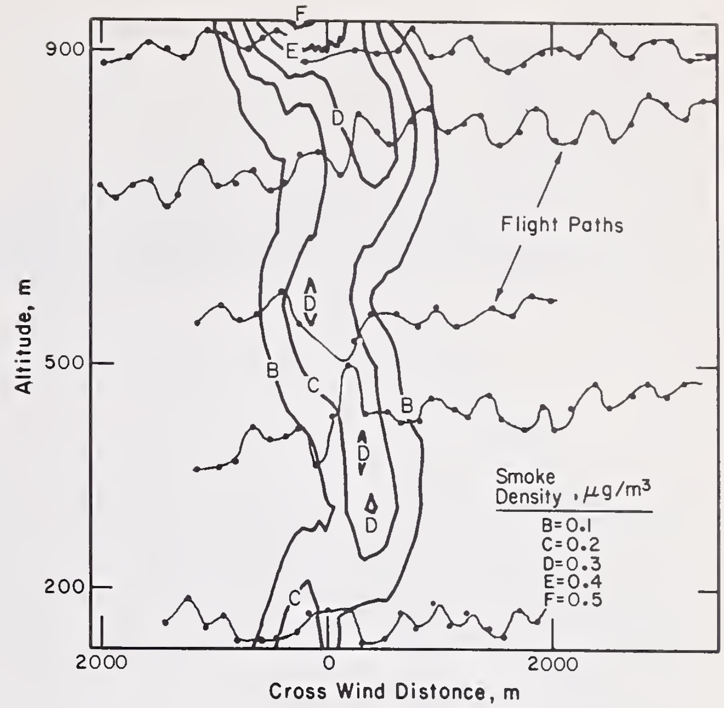

Figure 3.--Smoke plume density above the fire.

Figure 3 illustrates the density of smoke in the plume at five altitudes at a distance 1.6 km from the fire. The general shape of the cross section of the smoke plume is outlined by the contours of constant smoke density. At a distance of 1.6 km, the plume is denser and wider at the highest flight path. U.S. Weather Bureau soundings from Charleston, S.C., and Athens, Ga., indicated the height of the mixing layer was about 1000 m at 1900 EST on the day of the fire. Thus, it seems that under the low wind speed condition which prevailed during the fire, the majority of the buoyant plume quickly rose to the top of the mixing layer and diffused in an approximately Gaussian manner in the horizontal plane. However, the vertical smoke density profile does not seem to be a simple Gaussian model with diffusion from an apparent elevated source. The high centerline concentrations at the lower altitudes can be interpreted as leakage from the buoyant smoke column produced by the fire, or as multiple sources from the actively burning and burned-over, smoldering portions of the fire. In either case, it is clear that the character of smoke dispersion from a forest fire will vary with the stage of the fire's development, from a fairly hot fire that has just been set, through the stage of maximum combustion, to the stage of smoldering remnants.

Mathematical models for describing the smoke plume behavior during the fire are currently under development.

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Synoptic Scale Haziness over the Eastern U.S. and Its Long Range Transport[1]

N. V. Gillani and R. B. Husar[2]

Abstract -- The development and long range transport of synoptic scale haziness affecting much of the eastern U.S. is studied using daily visibility contours, air parcel trajectories and air quality data. It is shown that sulfates and ozone are major ingredients of the associated air pollution over large exposed areas.

1. INTRODUCTION

In-situ generation of secondary ozone and visibility-reducing aerosols during transport of the urban plume of St. Louis has been demonstrated to cause a significant deterioration of ambient air quality over a downwind range well in excess of the mesoscale (White, et al., 1976). The pollutant plume from a large coal-fired power plant near St. Louis has also been tracked downwind for nearly 300 km. (unpublished data of Project MISTT, 1976). These observations represent direct evidence of the long range transport of atmospheric pollution. Long range transport processes, acting simultaneously on effluents from a large number of sources, are believed to be largely responsible for the observed high levels of rural ozone (Ripperton, et al., 1975) and sulfates (EPA, 1975) over wide regions of the eastern U.S. The role of long range transport in regional air pollution phenomena is perhaps most vividly illustrated by the export of synoptic scale hazy air masses from a given source region to distant and wide areas of exposed receptor regions. Such synoptic scale polluted air masses ('blobs')[3] can develop over a region with substantial emissions from a large number of sources when meteorologically stagnant conditions (low wind speeds and/or mixing depths) persist over the region for several days. In this paper, we present the case study of a synoptic scale air pollution episode which resulted when a 'blob' formed in the industrialized northeastern region of the U.S. and continued its residence over various parts of the eastern half of the country for a period of nearly two weeks during the summer of 1975. In the exposed areas, the passage of the 'blob' was characterized by very low visibilities, high ozone levels and, based on limited available aerosol data, also high concentrations of fine particulates including sulfates. The existence of haziness on the scale of an entire synoptic air mass has recently been observed based on visibility reduction and suspended particulate data (Hall, et al., 1973), as well as on visual data from satellite studies (Lyons, 1975).

1/ Paper presented at the Fourth National Conference on Fire and Forest Meteorology, St. Louis, Missouri, Nov. 16-18, 1976.

2/ Air Pollution Research Laboratory, Mechanical Engineering Department, Washington University, St. Louis, Missouri 63130.

3/ Random House Dictionary (1966):
'blob' - an object, esp. a large one having no distinct shape or definition;
here, 'blob' - "large hazy air mass".

2. DATA BASE FOR THE ANALYSIS

Studies aimed at the investigation of spatial-temporal scales and pollutant variability of regional scale air pollution continue to be hampered by the lack of large-scale air quality network data. The National Air Surveillance Network (NASN) data for sulfates, for example, were available to us from about 60 stations in the eastern half of the U.S. These data consist of 24-hour sulfate concentrations based on hi-volume filter samples collected only once every 12 days. EPA's SAROAD data base was used for ozone concentrations (hourly average), recorded regularly at 89 local aerometric monitoring stations in the eastern U.S. An attractive qualitative surrogate for visibility-reducing aerosol data in studying the spatial extent and temporal behavior of large hazy air masses in the U.S. is the surface visual range observations made every hour at more than 300 airport stations of the National Weather Service (NWS) network (Service A). The high spatial density of this network permits the meaningful use of computer contour plotting techniques. Using the visibility data, the spatial extent, the temporal evolution and the transport of hazy 'blobs' may be followed for several days by inspection of chronological visibility contour maps. Daily weather maps prepared by the NWS and surface wind patterns, as well as long-range air parcel trajectories constructed from upper air network data (USAF-ETAC) are also used. Finally, detailed local air pollution data of aerosol mass, and sulfate and ozone concentrations are used whenever possible to check for consistency of the synoptic pollution patterns with such local measurements.

3. RESULTS

Visibility and Weather Maps:

Successive contour maps of noon visibility (Fig. 1) were plotted for each day from June 25 through July 5, 1975 (every second day shown). Noon visibilities were chosen to minimize the effect of the early morning ground fog on the visibility contours. For inland stations, the noon relative humidity commonly ranged between 50% and 80%. The visibilities used have not been corrected for relative humidity effects. The different shaded regions in the figure correspond to different observed visual ranges V(m), or equivalently, to different levels of light extinction coefficient b_{ext} (m^{-1}). The two quantities are related by (Middleton, 1952):

$$b_{ext} = \frac{3.912}{V} .$$

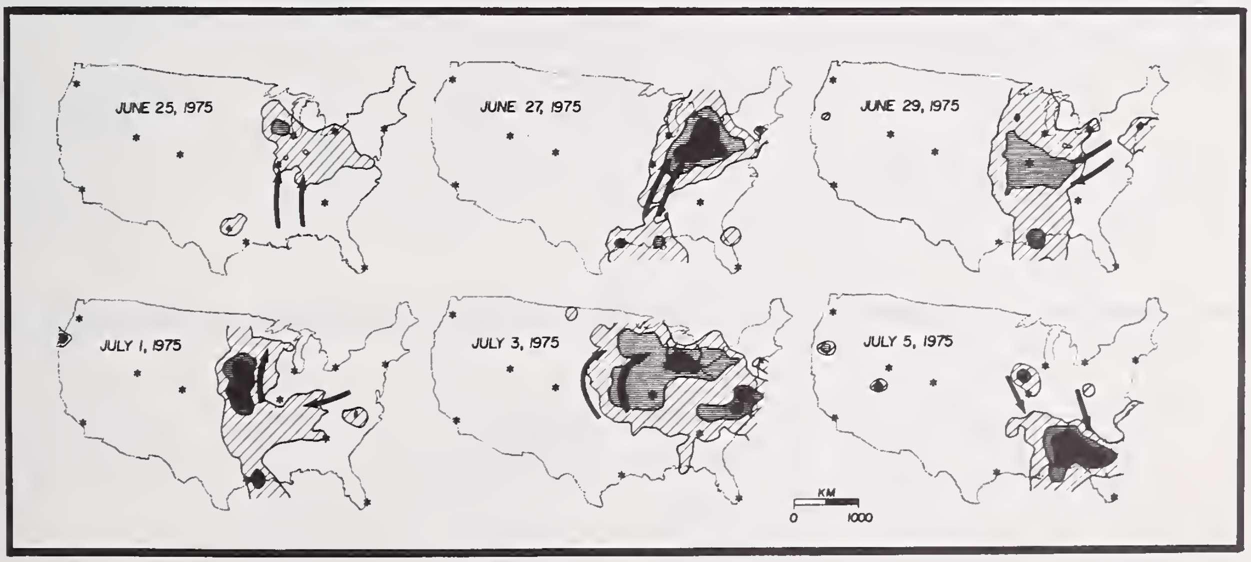

Figure 1. Sequential contour plots of noon visibility at ground level for the period June 25 to July 5, 1975. Contours are for b_{ext} = 4,6,8 ($10^{-4}m^{-1}$), corresponding to approximate visual ranges of 4-6 miles (light shade), 3-4 miles (medium shade), and <3 miles (black).

Inspection of the sequence of maps reveals that multi-state regions are covered with a haze layer in which the noon visibility is less than 6 miles ($b_{ext} > 4 \times 10^{-4} m^{-1}$).

The day-to-day motion of these hazy 'blobs', as revealed by direct inspection of the sequential plots, is checked for consistency by comparison with the long-range motion of corresponding air parcels. The long-range air parcel trajectories are computed using a computerized *post-facto* trajectory model (Heffter and Taylor, 1975) intended primarily for use in calculating pollutant transport on a regional scale. The calculated trajectories used here are at 6-hour intervals, backward for 3 days from any given destination, and use observed and interpolated winds averaged between 250 and 1000 m above average terrain. From long-range air parcel trajectory calculations and surface wind information, it was determined that the air mass of June 25, within which the visibility was less than 6 miles, was of maritime origin in the Gulf of Mexico (see Fig. 3A). This air mass had been transported in a northerly flow across Louisiana, Arkansas, Illinois and Indiana. Between June 25 and 27, a NNE trajectory prevailed in the southern states, but relative stagnation prevailed in the southern Great Lakes and Ohio River valley region. In this region of stagnation, the air mass became increasingly hazy, presumably as a result of accumulating pollution from the high pollutant emission-density of this region of the U.S.

The daily weather maps for the period June 29 through July 4, 1975 are shown in Fig. 2. A major feature of the weather system during that period was the tropical storm "Amy", moving up off the northeast coast. By its presence, the tropical storm provided a barrier against large scale eastward motion. From the northwest, a front was approaching the Great Lakes. Between June 28 and 30, as the storm advanced north, an easterly flow developed inland, causing the hazy air mass to drift slowly westward, passing over St. Louis, MO on June 28-29 (see Fig. 3B) and continuing across Missouri and Kansas (June 30). Midday visibilities over eastern Missouri deteriorated to less than 3 miles at the peak of the episode. Weather satellite pictures of the area on June 30 revealed the presence of the hazy air mass in the same region as that obtained by visibility contour plotting (Lyons and Husar, 1976). From June 30 to July 2, the hazy air mass moved in the clockwise circulating wind pattern (associated with the high pressure

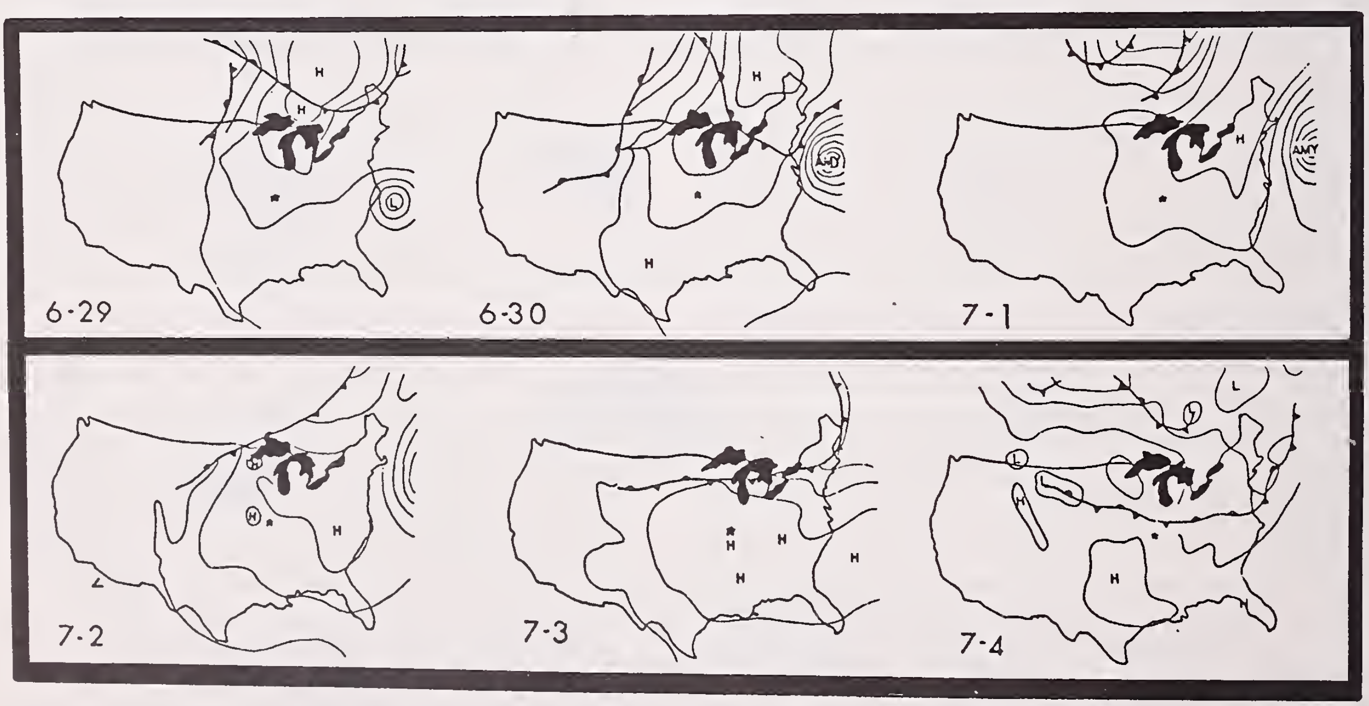

Figure 2. Daily U.S. weather maps, June 29 - July 4, 1975.

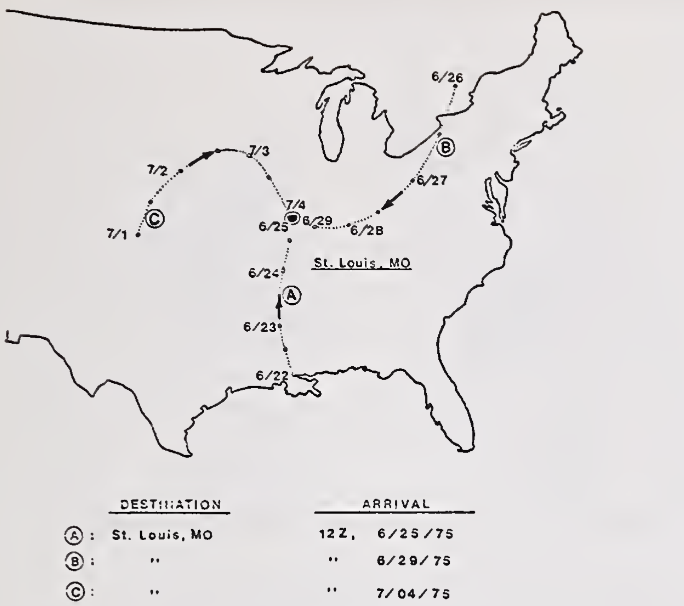

Figure 3. Three-day backward air trajectories arriving in St. Louis.

Figure 4. Three-day backward air trajectories arriving at destinations shown.

region below the front) up and around to the southern Great Lakes region (see Fig. 4A,B). In the meantime, pollutant emissions continued into this high pressure region. By July 3, the Canadian front had itself reached the southern Great Lakes, and it formed the northern border of a massive hazy blob occupying most of midwestern and northeastern U.S. Once again, the visibility deteriorated to less than 3 miles near St. Louis, MO. In the next two days, the cold front rapidly advanced southward, passing over St. Louis on July 4 and continuing on. As the front advanced, the hazy blob was pushed ahead of it (see Figs. 3C and 4C). By July 5, the blob was in southeastern U.S., and the visibility was less than 4 miles over Atlanta, GA, Birmingham, AL, and Tallahassee, Fl.

Sulfate and Ozone Maps:

There exists a strong correlation between aerosol mass concentration in the size range of 0.1 to 1 μm diameter and the extinction of light by scattering (Charlson, 1969; Hidy et al., 1974). Furthermore, measurements in and near St. Louis, MO have shown that sulfates often account for 50% or more of the aerosol mass in this size range (Charlson et al., 1974). The significance of the use of visibility data as a surrogate for atmospheric pollution may thus be checked by direct comparison of the visibility maps with corresponding maps for sulfate. NASN sulfate data were available for June 23 and July 5, 1975. These are shown plotted in Fig. 5 in the form of contours over the eastern half of the U.S. The contours are hand-plotted because the density of data points was judged too sparse to justify computer plots. Direct comparison of visibility and sulfate maps for the two days clearly shows a substantial positive correlation between the two. Sulfate concentrations in excess of 30 $\mu g/m^3$ are seen to coincide with regions of lowest visibility.

During the period considered in the present case study, insolation was generally above seasonal norms. Under similar conditions, high rural ozone levels have been observed in conjunction with high concentrations of light scattering aerosols (White et al.,1976). In order to examine the correlation between ozone and visibility reduction on a synoptic scale, contour plots were also prepared (by hand) for ozone for the period June 25 through July 3,1975 (Fig. 6). Ozone values shown are daily maximum levels which are attained in the early afternoon. The plots show that the U.S. standard concentration for ozone (0.08 ppm) was exceeded over large areas of the eastern U.S. on all days of the air pollution episode.

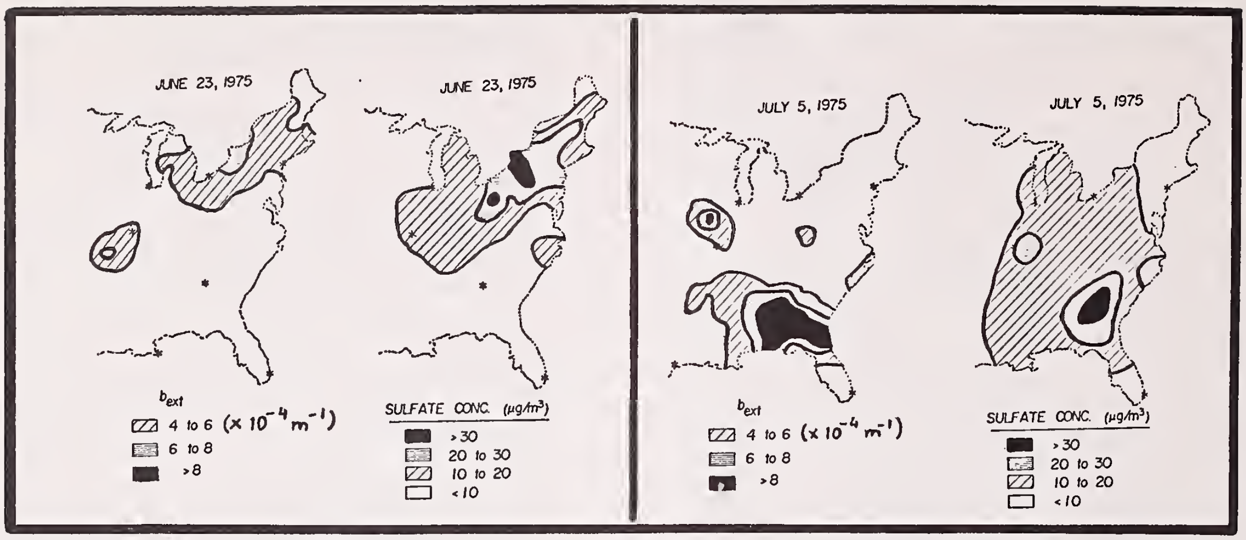

Figure 5. Comparison of contour plots of noon visibility reduction (b_{ext}) and 24-hour sulfate concentration for 6/23 and 7/5/1975.

Comparison of the maps for visibility and ozone (Figs. 1 and 6 respectively) reveals that the geographical location of high ozone concentrations roughly corresponds to the areas of low visibility (and high sulfate). As may be anticipated, however, the correlation with haziness (low visibility) is much better for sulfates than for ozone.

Local Air Pollution Data (St.Louis,MO):

Data for ozone and light extinction coefficient tor St. Louis, MO are shown in Fig. 7 for the entire summer of 1975. The surface ozone data exhibit the typical diurnal pattern consisting of near-zero readings during the night and early morning , and peaks in the early afternoon followed by a drop during the evening hours. The two passages of the hazy blob over St. Louis are confirmed by the elevated peaks for both ozone and b_{ext} during the periods June 27-29 and July 2-4.

The two episodes of air pollution in St. Louis during the period of the case study are also evidenced by the data of light scattering coefficient (b_{scat}) measured locally using integrating nephelometers (Fig. 8a). The data were collected at three widely-spaced local air monitoring stations. One of the stations is situated in the city (station 4), one on the outskirts of the city (station 9), and one at a background location (station 6) about 40 km to the west of the city. The data from all three stations reveal a common temporal pattern of atmospheric fine particulate loading, thus confirming that

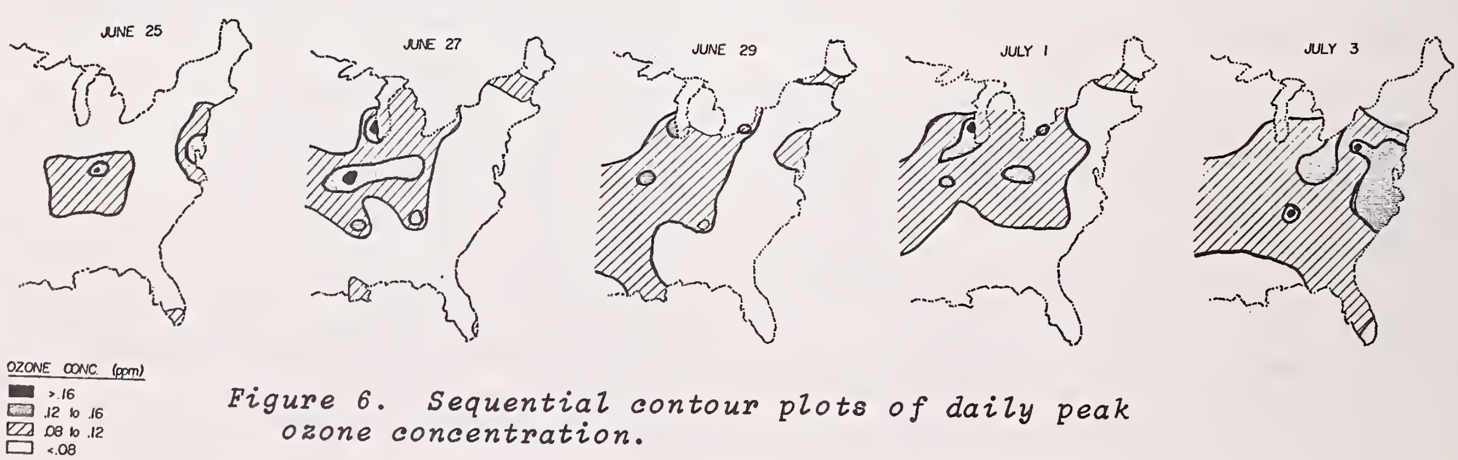

Figure 6. Sequential contour plots of daily peak ozone concentration.

the major changes in the light scattering coefficients during the entire period occurred over a spatial scale substantially greater than that of the St. Louis metropolitan area. These data also indicate that the increase in the light scattering aerosol concentrations during this period were the result of external inflow rather than of local source contributions. Fig. 8b shows the temporal variations of the light extinction coefficient computed based on observed visibility ranges at the major airports of St. Louis, MO and Springfield, IL. The two observation sites are about 150 km apart. Both traces reveal the two passages of the blob whose spatial scale is larger than the separation of the sites. The time offset of the two traces is much smaller than the temporal scale of each blob passage over the region, and is due to the separation of the sites. Comparison of Figs. 8a and b reveals a close correlation between the actual measured light scattering coefficieint (b_{scat}) and the light extinction coefficient (b_{ext}) inferred from visibility data. This correlation demonstrates the utility of visibility observations as a qualitative surrogate for aerosol concentration of the atmosphere.

The daily average sulfate concentrations using Hi-Volume filters were measured before, during, and after the passage of the hazy air mass over St. Louis, MO. Hi-Volume filter samples, collected every six days by the St. Louis County Department of Health, were analyzed for particulate sulfur using flash volatilization-flame photometric detection method (Husar et al.,1975). An increase from 9.2 μgm^{-3} on June 23 to 32.7 μgm^{-3} on June 29 is shown in Fig. 8a. The sulfate content then dropped to 8.0 μgm^{-3} on July 5 after the passage of the Canadian front. Sulfate accounted for 19% of total aerosol mass before, 34% during, and 15% after the passage of the hazy air mass. The daily average sulfate concentrations were compared to daily average b_{ext} (uncorrected for relative humidity effects) for the entire summer (June, July, August 1975). The correlation coefficient was found to be r = 0.7 and the regression equation for sixteen points was

$$b_{ext}[10^{-4}m^{-1}] = 3.24 + 0.11\ SO_4^{--}[\mu gm^{-3}].$$

These results tend to suggest that a substantial fraction of the haze aerosol, particularly during the passage of 'blobs', was associated with sulfates.

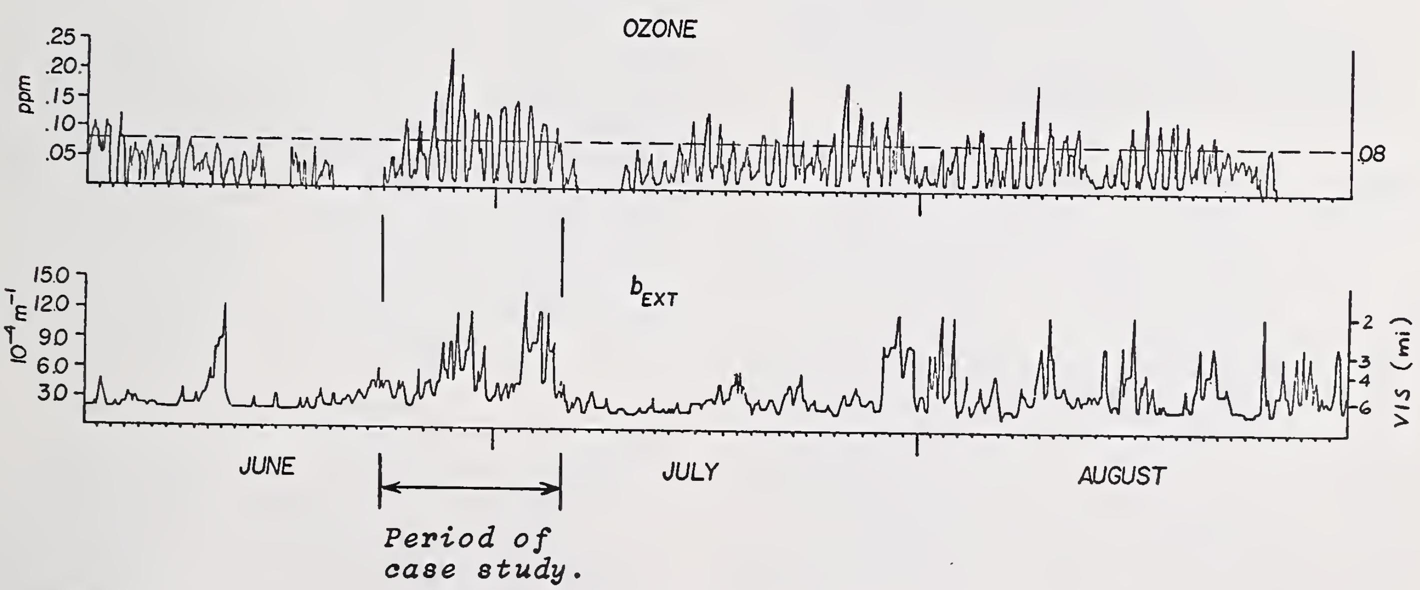

Figure 7. Comparison of long-term observations of ozone light extinction coefficient at an air monitoring station in St. Louis, MO.

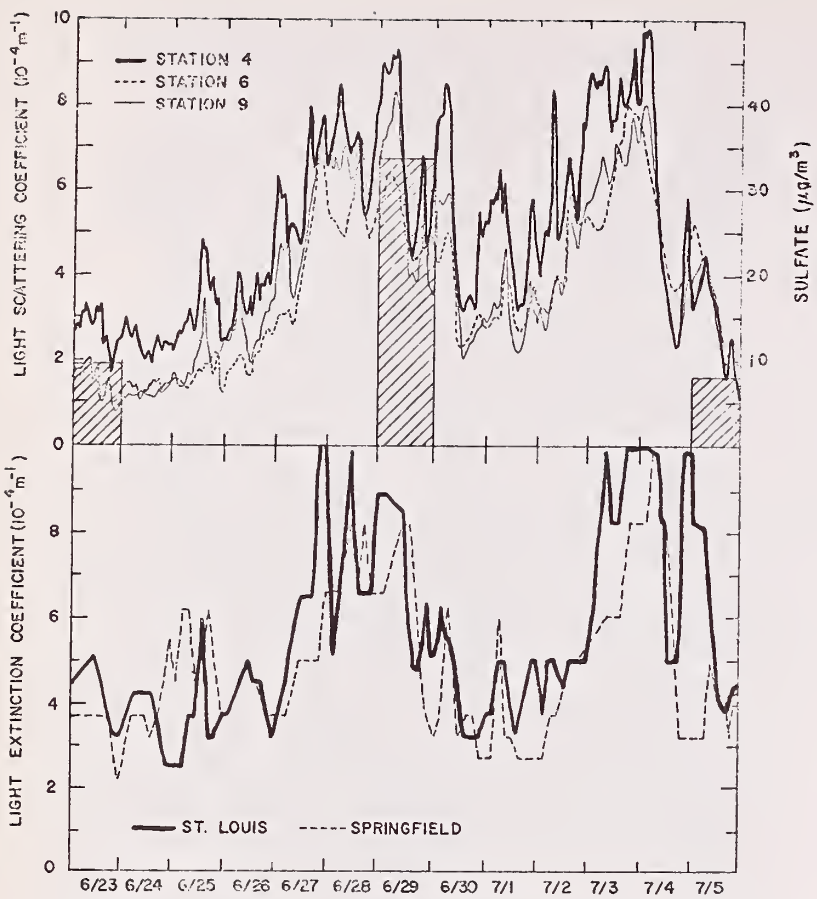

Figure 8. a) Light scattering coefficient, b_{scat}, recorded by nephelometers at three stations of the St. Louis City/County air monitoring network. Similar b_{scat} records (not shown here) were also recorded at the other stations in the network; b) Light extinction coefficients, b_{ext}, determined from visibility observations at St. Louis Lambert Airport and Springfield, IL Airport (150 km apart).

Effect of Relative Humidity:

As stated earlier, no corrections have been made to the visibility data for the contribution of relative humidity. However, the plots correspond to visibility observations at noon when the reduction of visibility due to fog or "water haze" is minimal. To investigate the effects of geographical location as well as relative humidity on local visibility observations, all hourly data for visibility and relative humidity for the entire period of June, July and August of 1975 were plotted for four widely-spaced stations, as shown in Fig. 9. For all four stations, the change in b_{ext} is small for increasing R.H. up to about 75%. For higher values of R.H., there is a sharp reduction of visibility. Thus, visibility reduction is mostly due to pollution for R.H. less than 75%, and substantially due to water vapor for R.H. above 75%. Also, average summer visibility due to pollution (R.H.<75%) is much lower at Huntington, W.VA than at San Antonio, TX. The distribution of haziness over the entire U.S., seasonally averaged for the summer months, and considering only those local observations which correspond to R.H. in the range of 60-70%, is shown in Fig. 10. The lowest visibilities are observed to be in the northeastern section of the U.S., with the worst conditions prevailing in the region of the Ohio River valley. This is also roughly the region of highest emission density of SO_2 in the U.S., indicating the possible dominance of aerosols of anthropogenic origin in causing visibility reduction at R.H. below about 70%.

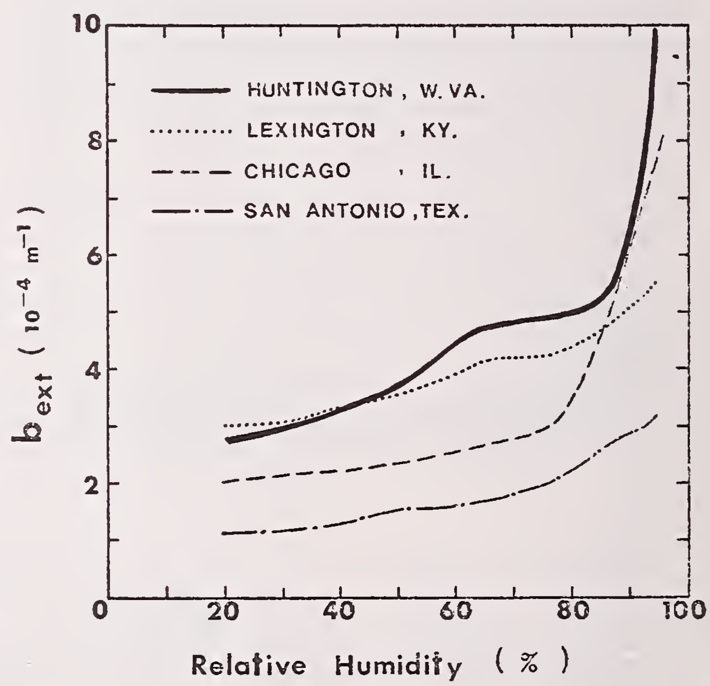

Figure 9. Light extinction coefficient in four U.S. cities for different ranges of relative humidity during Summer 1975. b_{ext} is determined by averaging all observations (for entire summer) which are in given RH ranges (e.g. 20-30%, 30-40%, and so on).

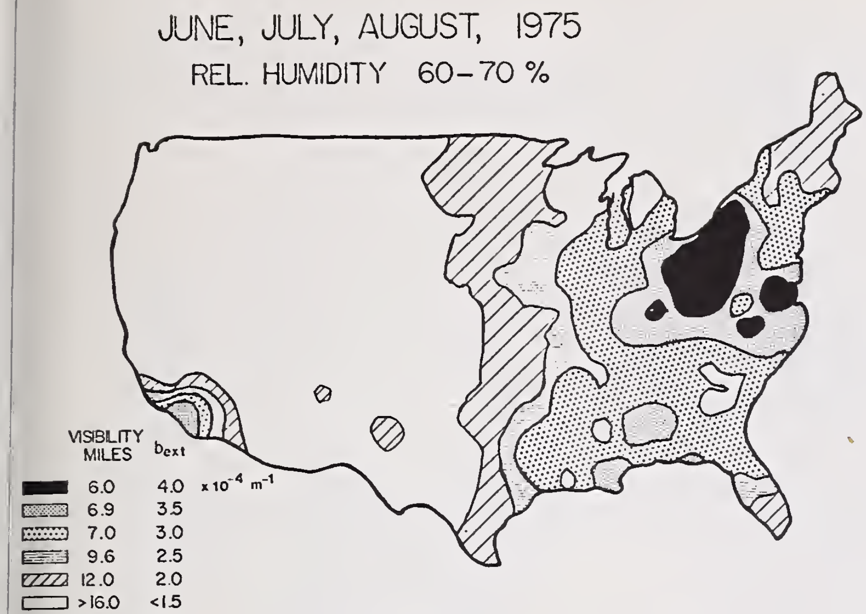

Figure 10. Geographical variation of b_{ext} for RH = 60-70% during summer 1975.

CONCLUSION

This brief analysis of national visibility data, synoptic weather maps, air parcel trajectories and national as well as local air quality data, points out two intriguing phenomena. Multi-state scale haziness may be caused by the accumulation in the atmosphere of pollutant emissions from one region and its subsequent transport over a long range. Secondly, a major fraction of the pollutant content of such large hazy air masses is constituted of secondary ozone and aerosols, mainly sulfates. Evidently, the role of meteorology is important in the occurrence of such regional scale pollution episodes lasting many days, even weeks. A much more intriguing question may be raised concerning the possibility of synergism between the ozone and sulfate contents of such polluted air masses. What is the role of such interactions in the origin and spread of such large scale air pollution episodes?

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